

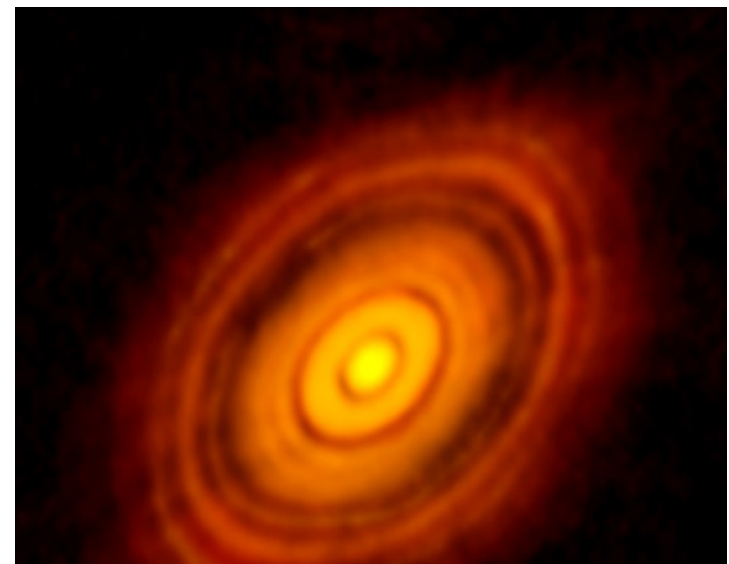
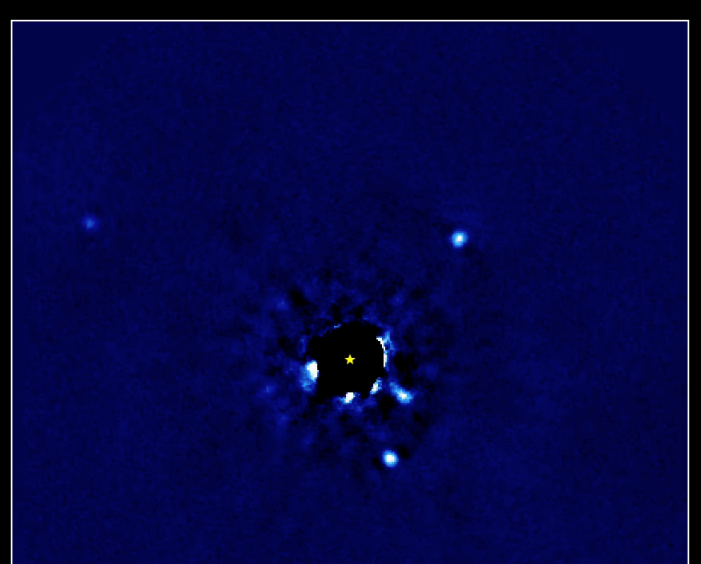


Jet Propulsion Laboratory
California Institute of Technology

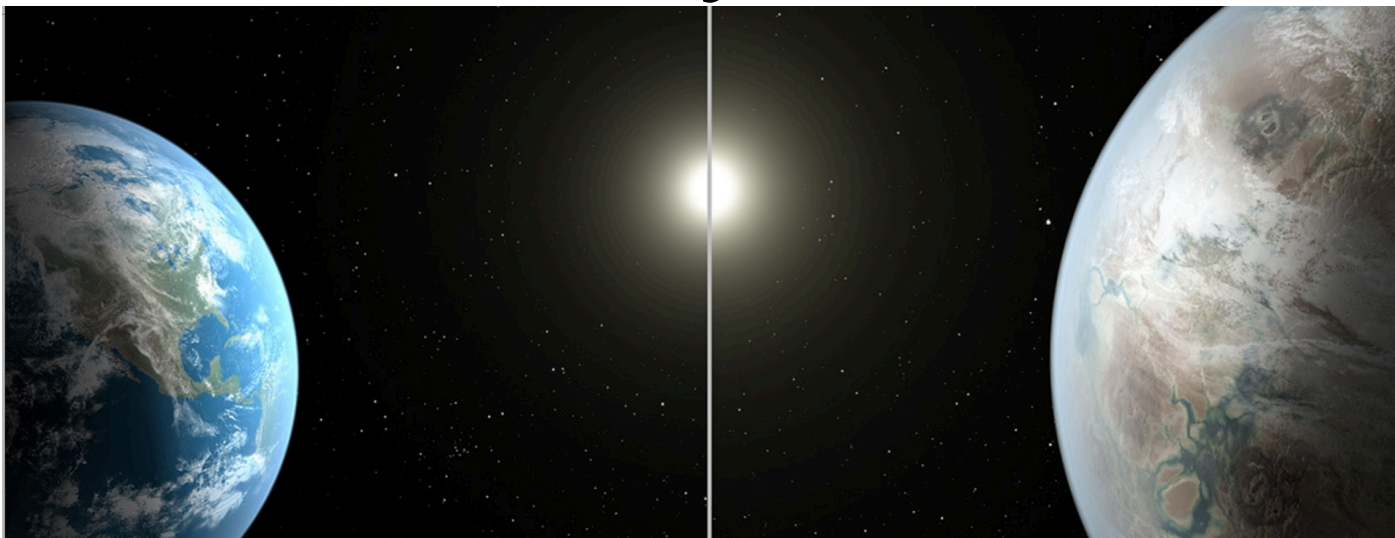
Planetary Magnetic Fields: Planetary Interiors and Habitability

Joseph Lazio

Thanks to W. M. Farrell, P. Zarka, G. Hallinan, E.
Shkolnik, W. M. Keck Institute for Space Studies
(KISS) Study team, Thomas Jefferson high school
students



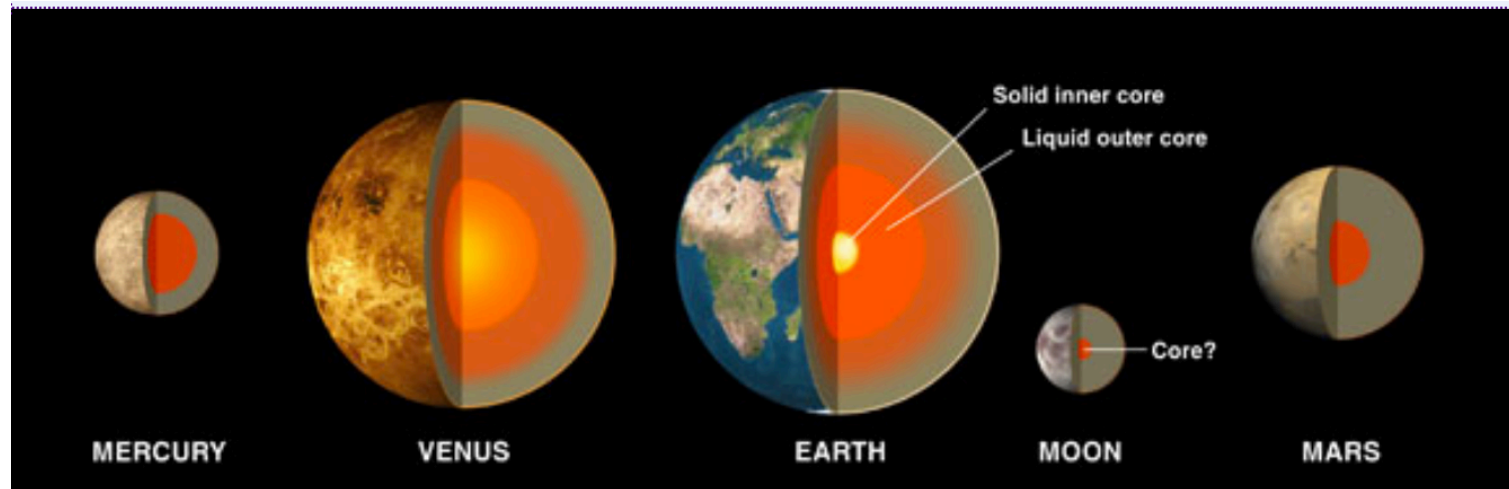
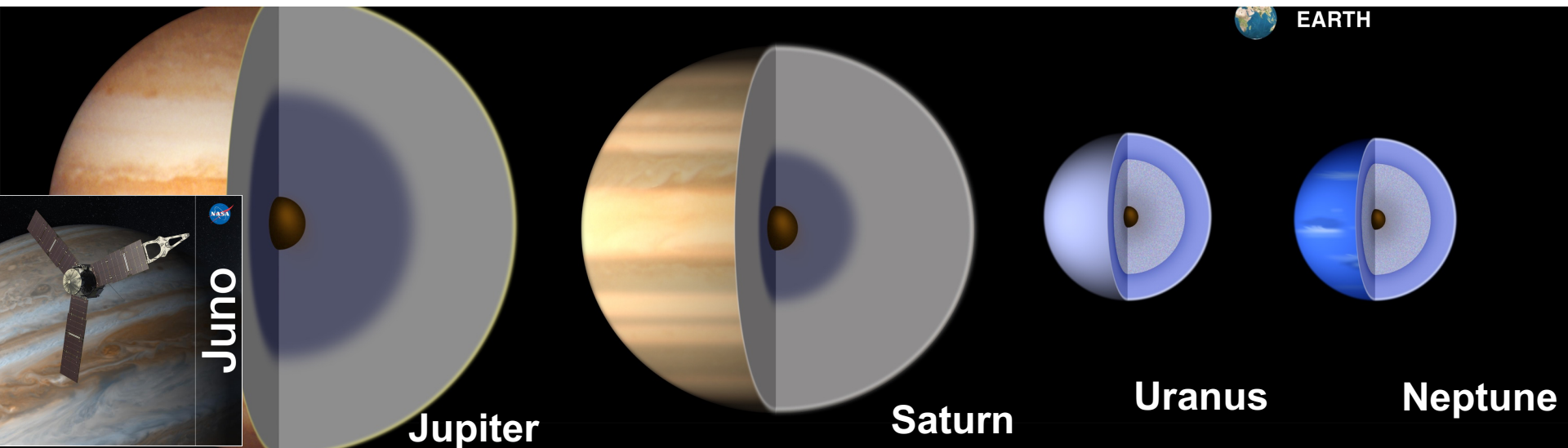
Act I: Magnetic Fields a.k.a. Why Do We Care?



Credits: J. Wang & C.
Marois; ALMA
(NRAO/ESO/NAOJ); C.
Brogan, B. Saxton
(NRAO/AUI/NSF); JPL, CIT

Planetary Interiors and Magnetic Fields

Solar System Guidance

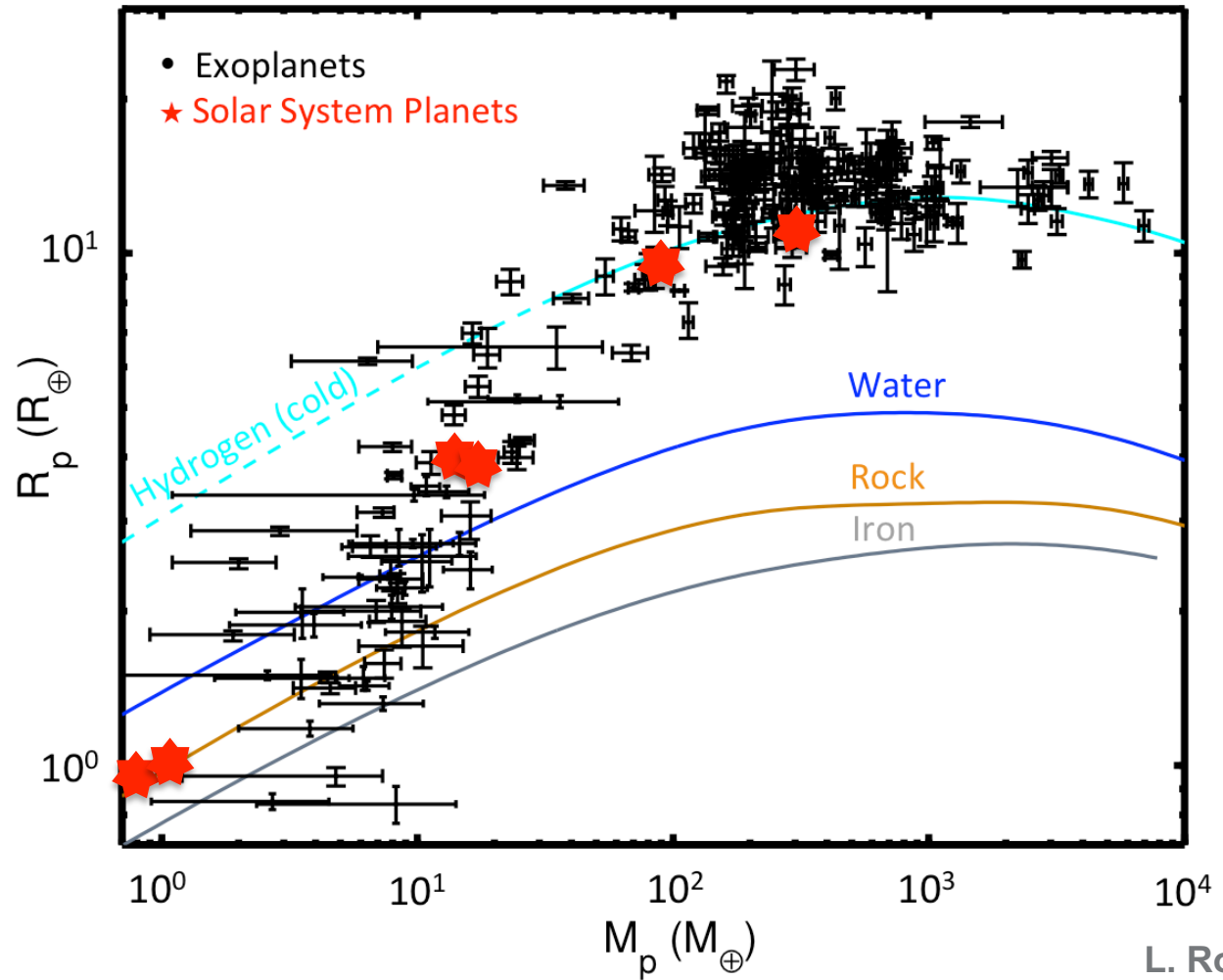


Planetary Interiors

Mass-Radius Relation → Mass-Radius-Magnetic Field Relation?

Mass from
radial velocity

Radius from
transit

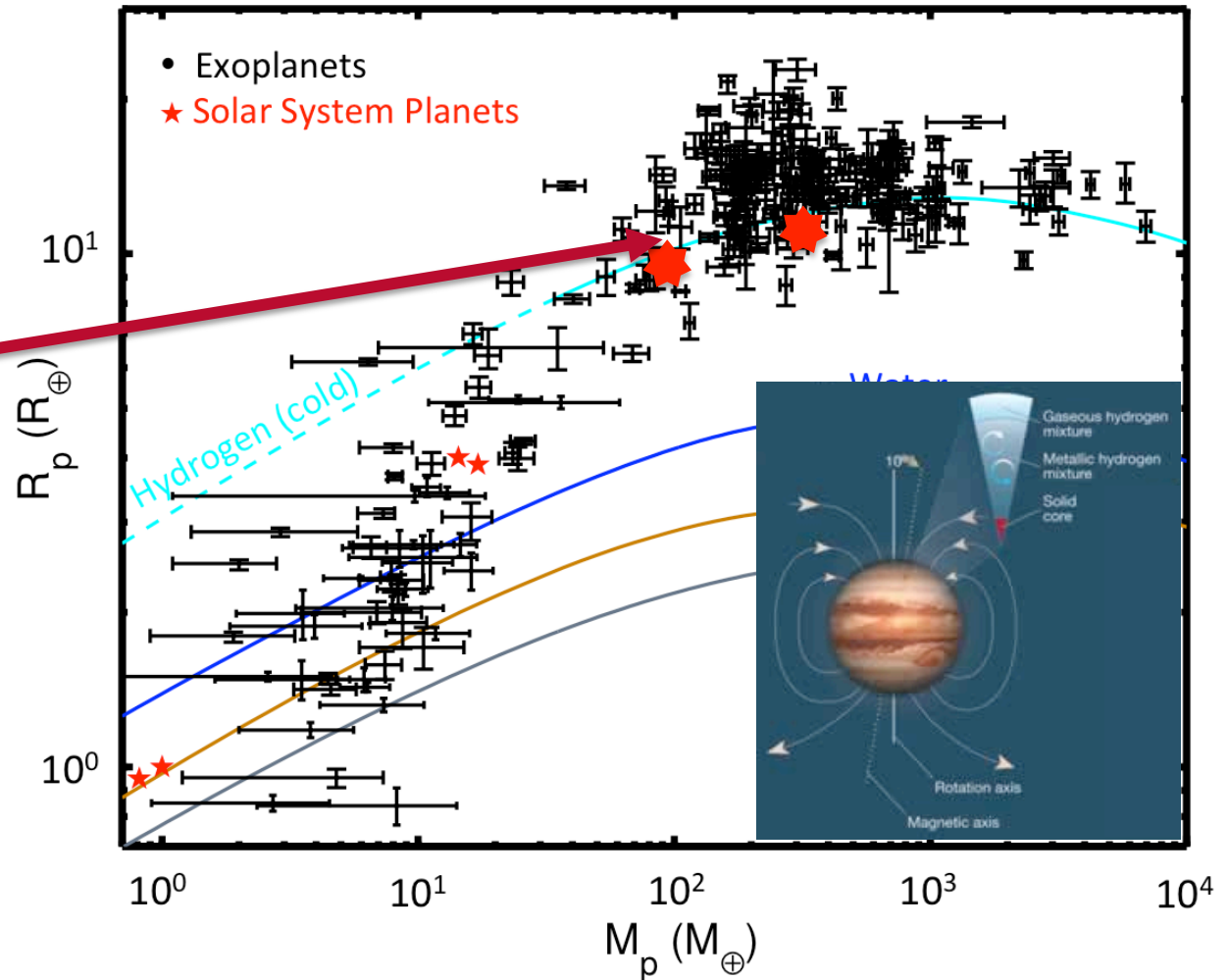


L. Rogers

Planetary Interiors

Jovian Planets

- Hydrogen is metallic at $P > \sim 25$ GPa
- Convective at depth
- *Should have magnetic fields; wrong if absent*



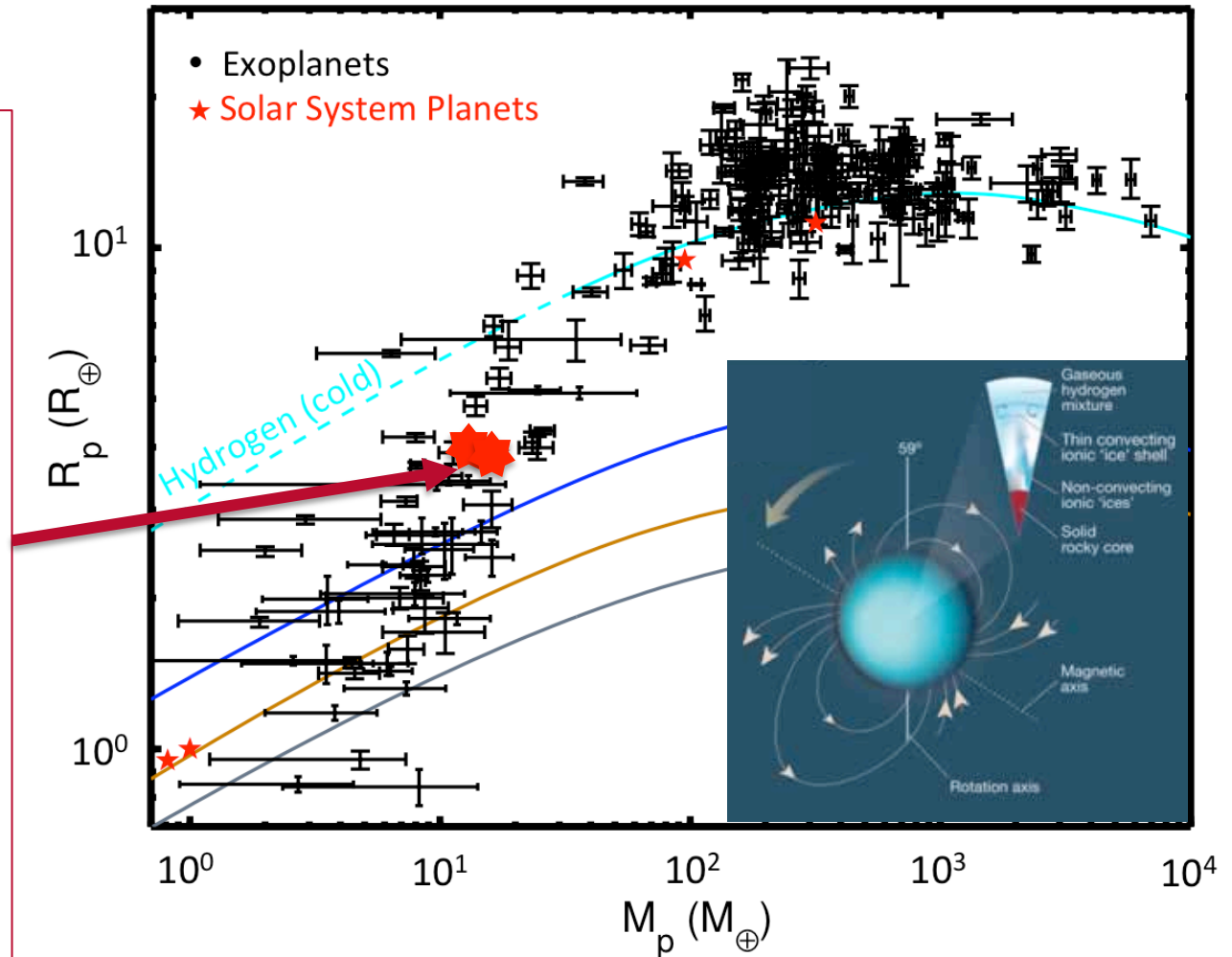
Planetary Interiors

Ice Giants

Water electrically
conducting $>\sim$
1000 K

➤ Neptune-like
planets *should*
sustain
planetary-scale
dynamos

∴ Detection of
magnetic field
would confirm
composition as
substantially
water



Planetary Interiors

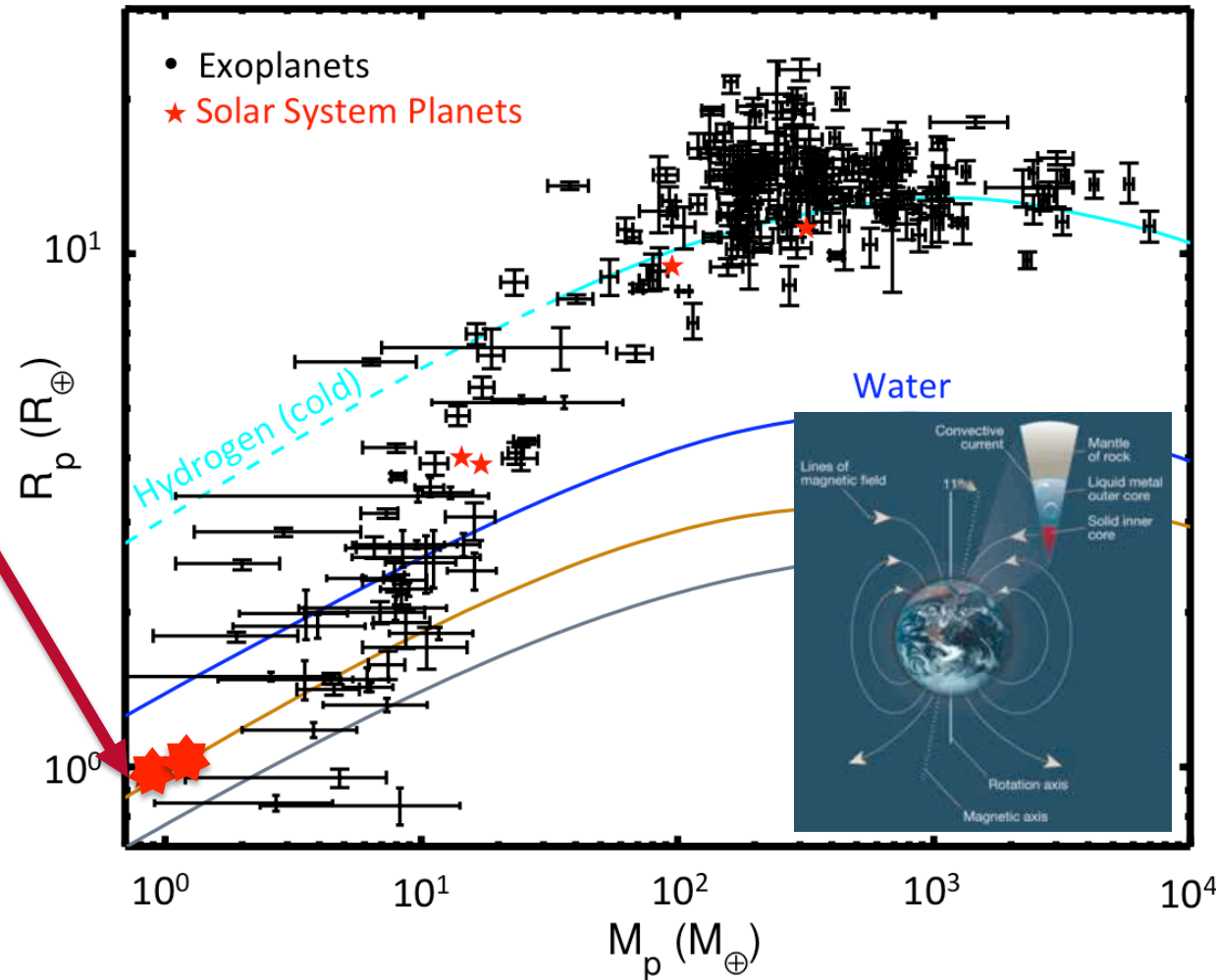
Terrestrial-Mass Planets

Not guaranteed to have convecting, conductive Fe-liquid cores

- SiO mantle+Fe core *or* Si-Fe-O mantle?
- Core (partially) solid? (volatile concentration)

❖ Marginal convective energy budget in Earth's core

- $T > 1500$ K
- Stronger tidal heating
- Higher concentration of radio nuclei
- Thick H/He envelope or stagnant lid tectonics



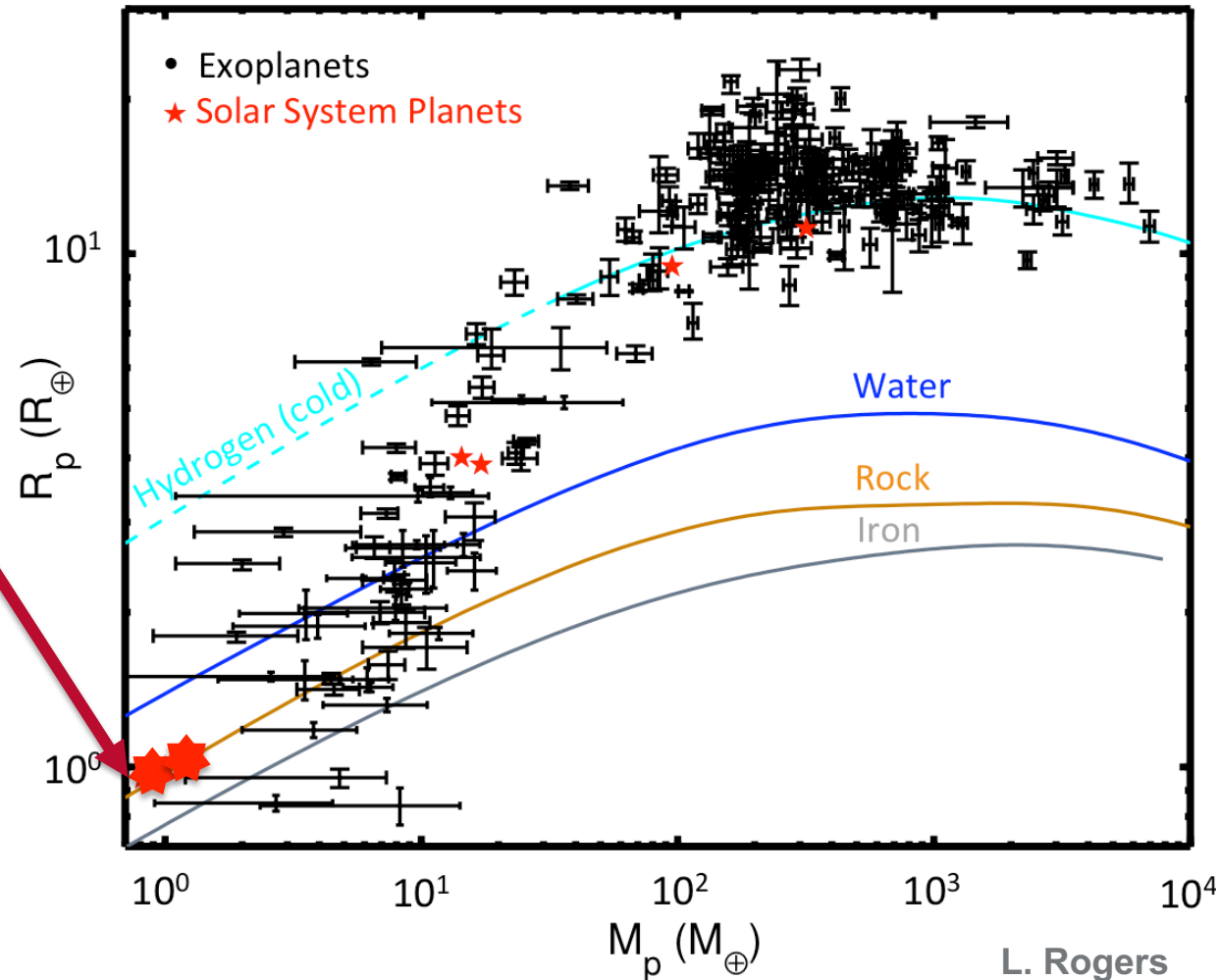
Planetary Interiors

Terrestrial-Mass Planets

Not guaranteed to have convecting, conductive Fe-liquid cores

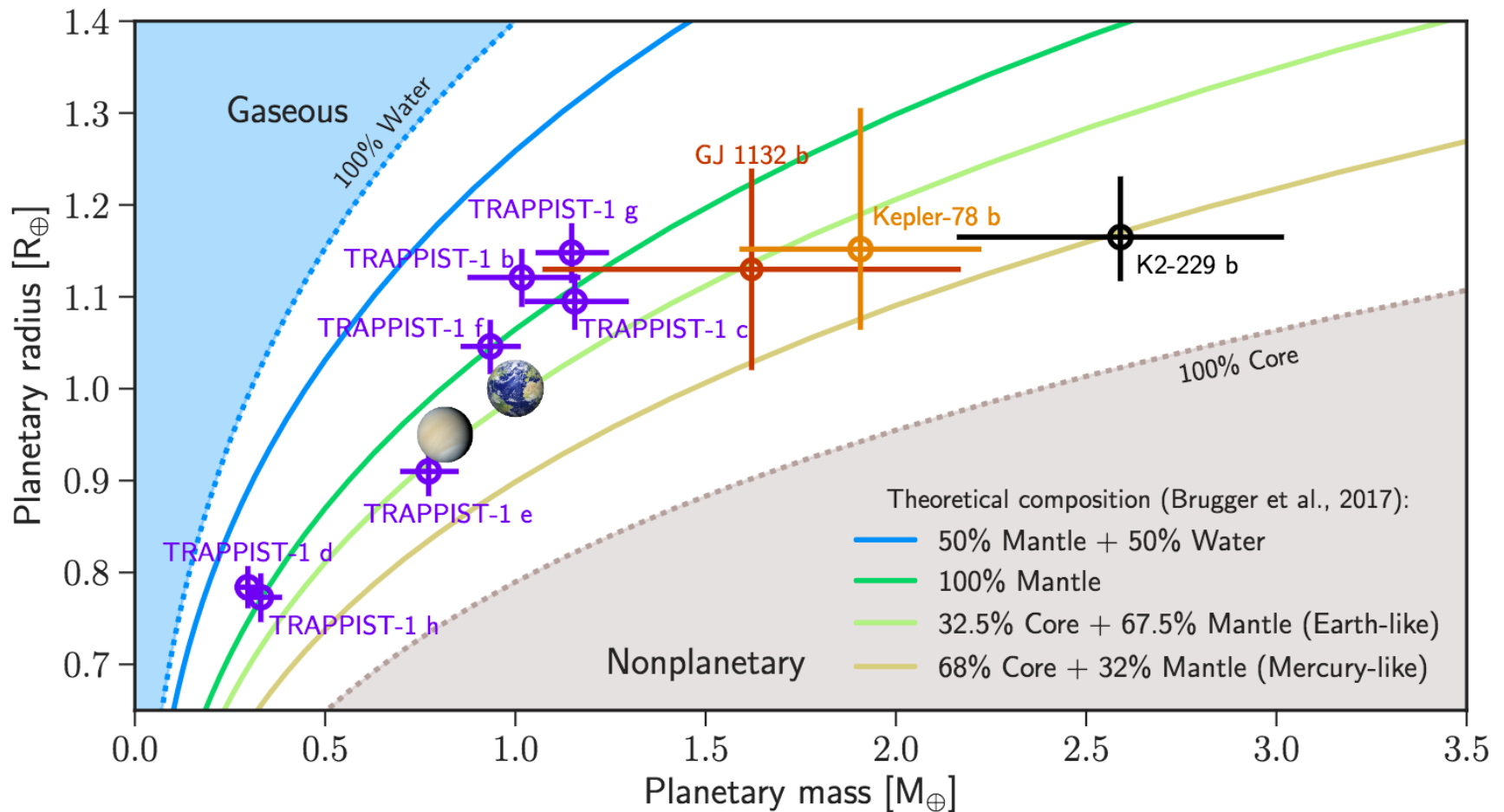
- SiO mantle+Fe core or Si-Fe-O mantle?
- Core (partial) solidification?

- ❖ Marginal convective energy budget in Earth's core
- Magnetic field measurement constrains planet's thermal evolution, energy budget, may indicate plate tectonics



An Earth-sized exoplanet with a Mercury-like composition

Santerne et al.; arXiv:1805.08405



A fertility company that
defines the textbooks p. 609

Multigenerational effects
on development pp. 634 & 657

Microbial ecology and
evolution pp. 649 & 663

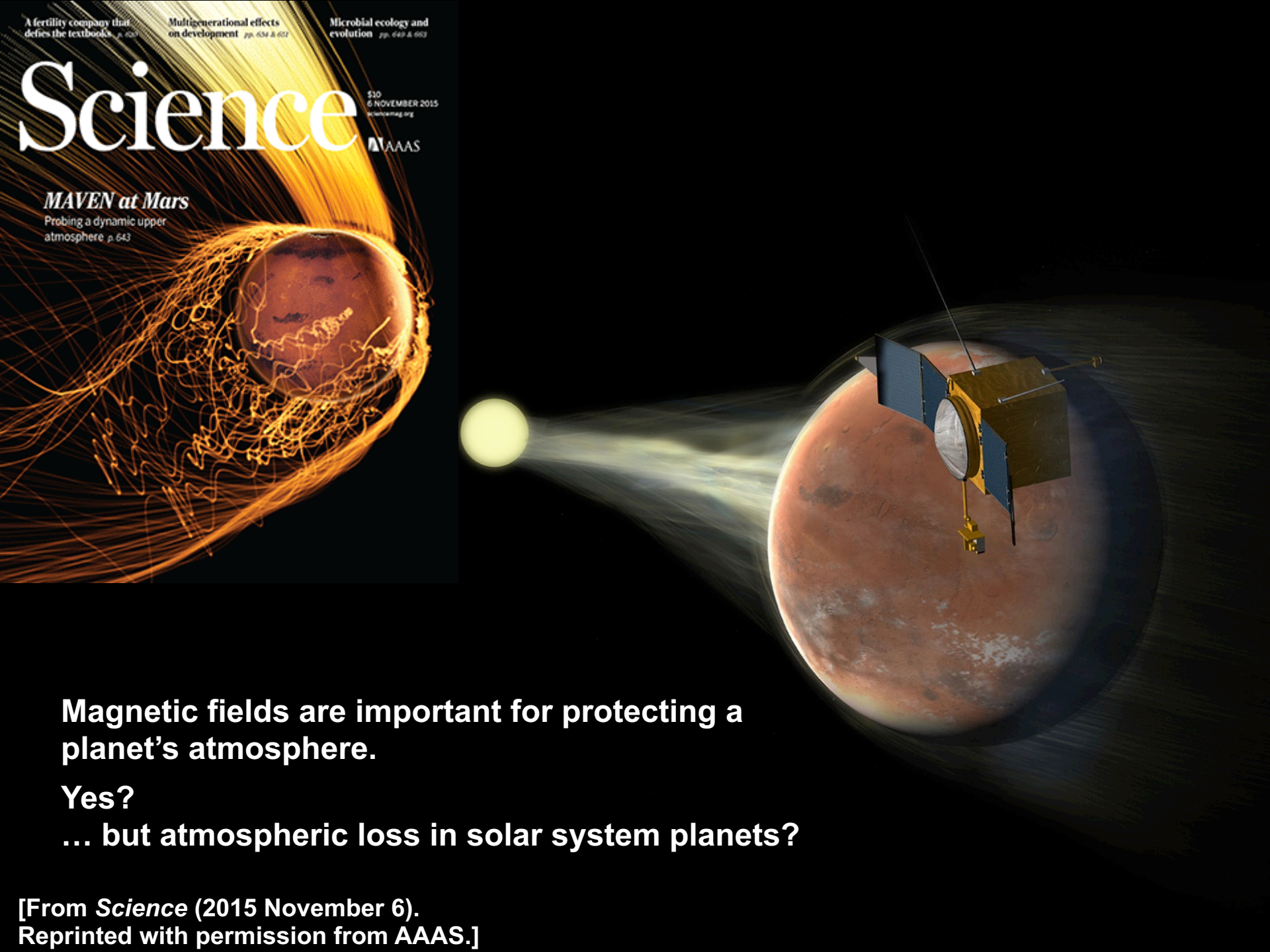
Science

\$10
6 NOVEMBER 2015
sciencemag.org

AAAS

MAVEN at Mars

Probing a dynamic upper
atmosphere p. 643

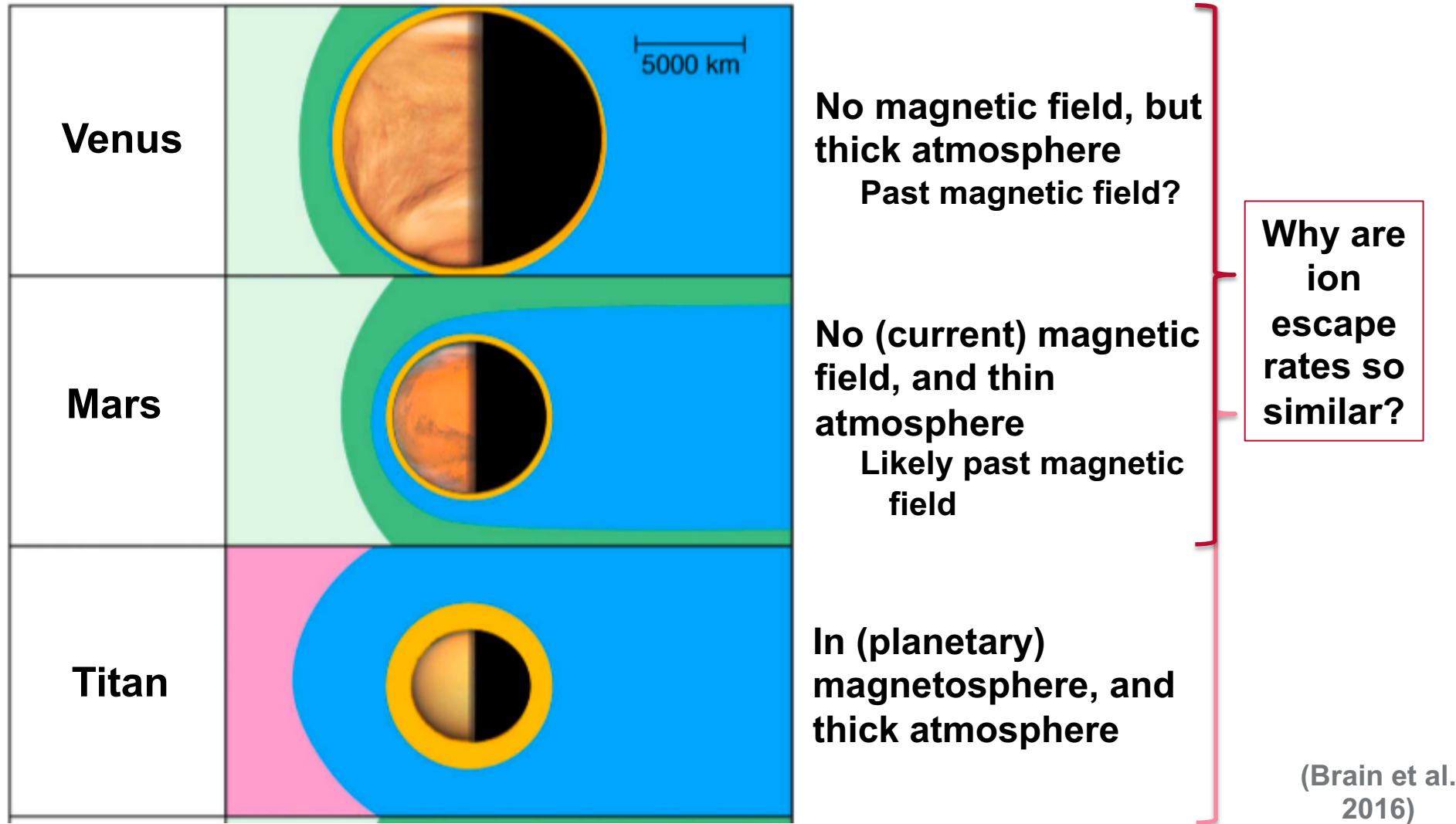


Magnetic fields are important for protecting a planet's atmosphere.
Yes?
... but atmospheric loss in solar system planets?

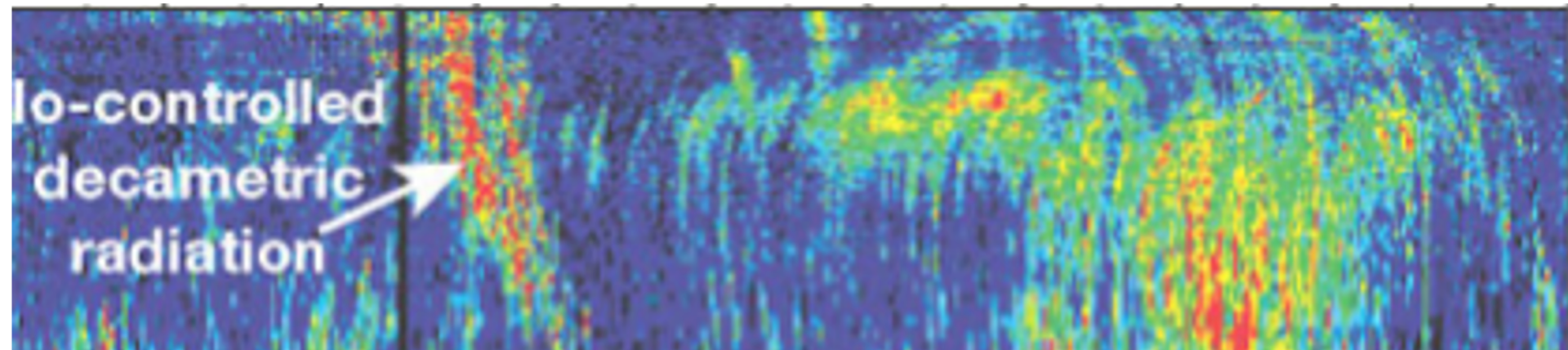
[From *Science* (2015 November 6).
Reprinted with permission from AAAS.]

Magnetic Fields and Atmospheric Escape?

What is the role of magnetic fields?

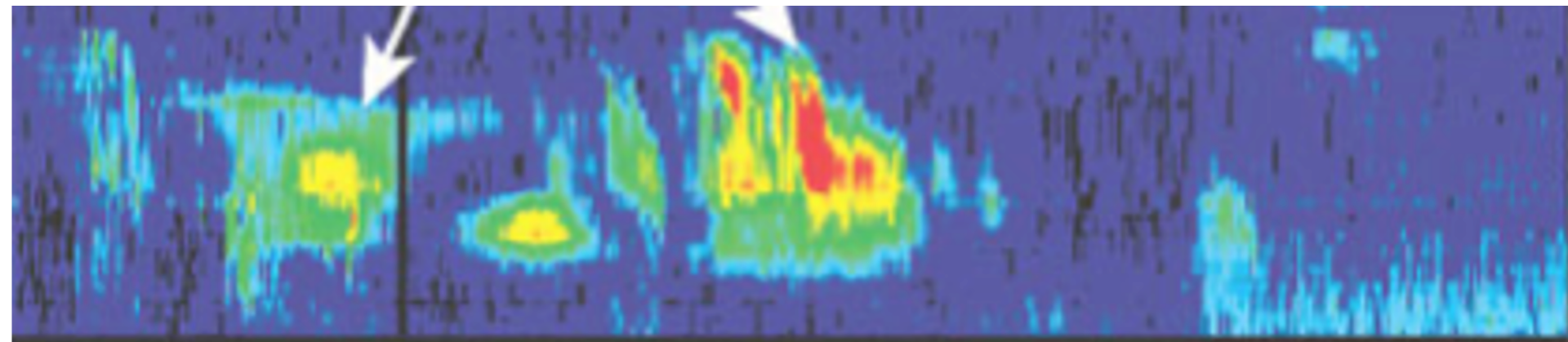


(Brain et al.
2016)

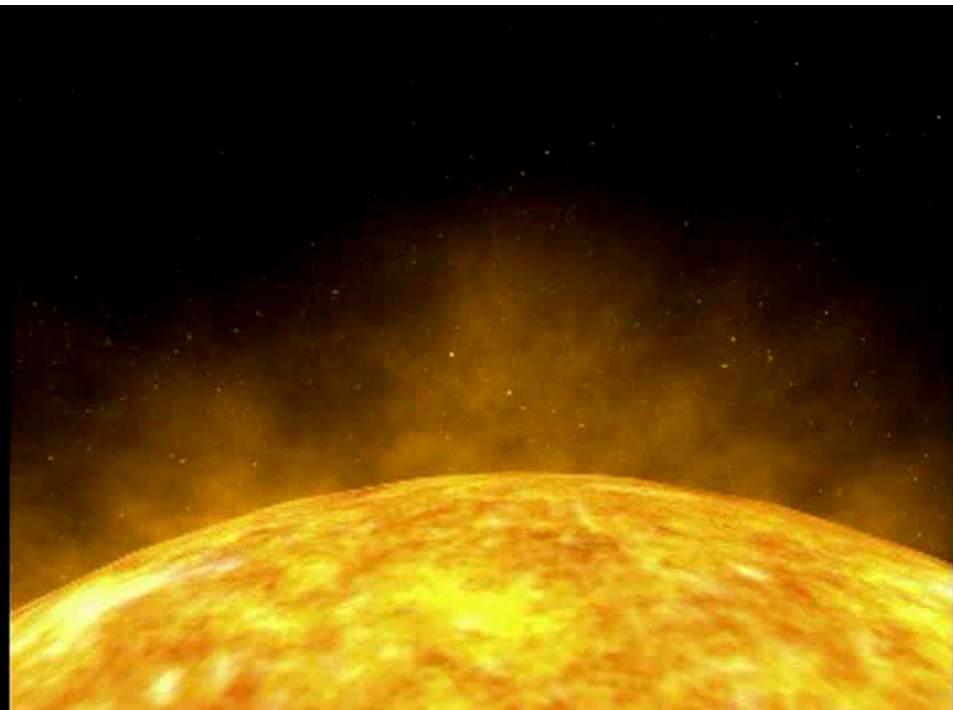


Act II

Magnetic Fields and Radio Emission



Electron Cyclotron Maser Radio Emission

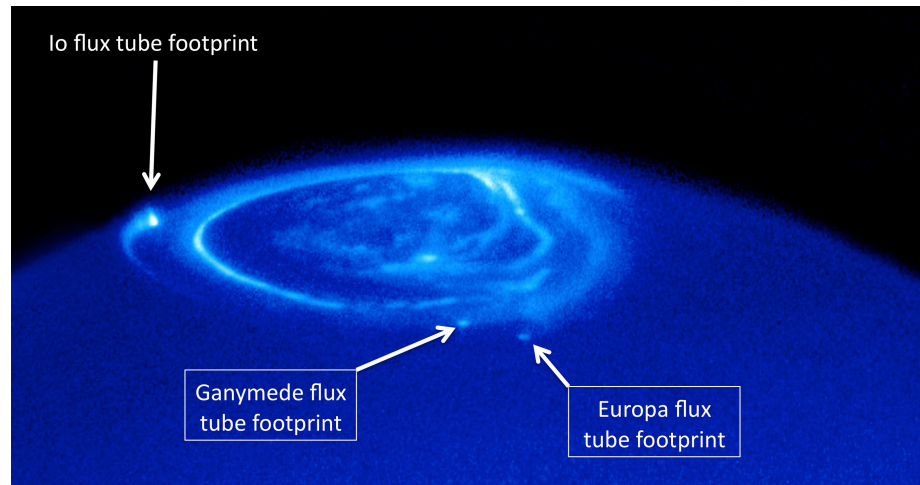
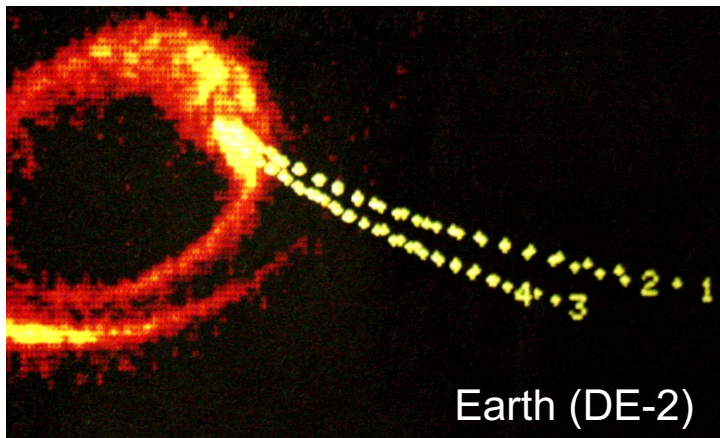


Stellar wind provides energy source to magnetosphere

~ 1% of input energy to auroral region emitted in UV

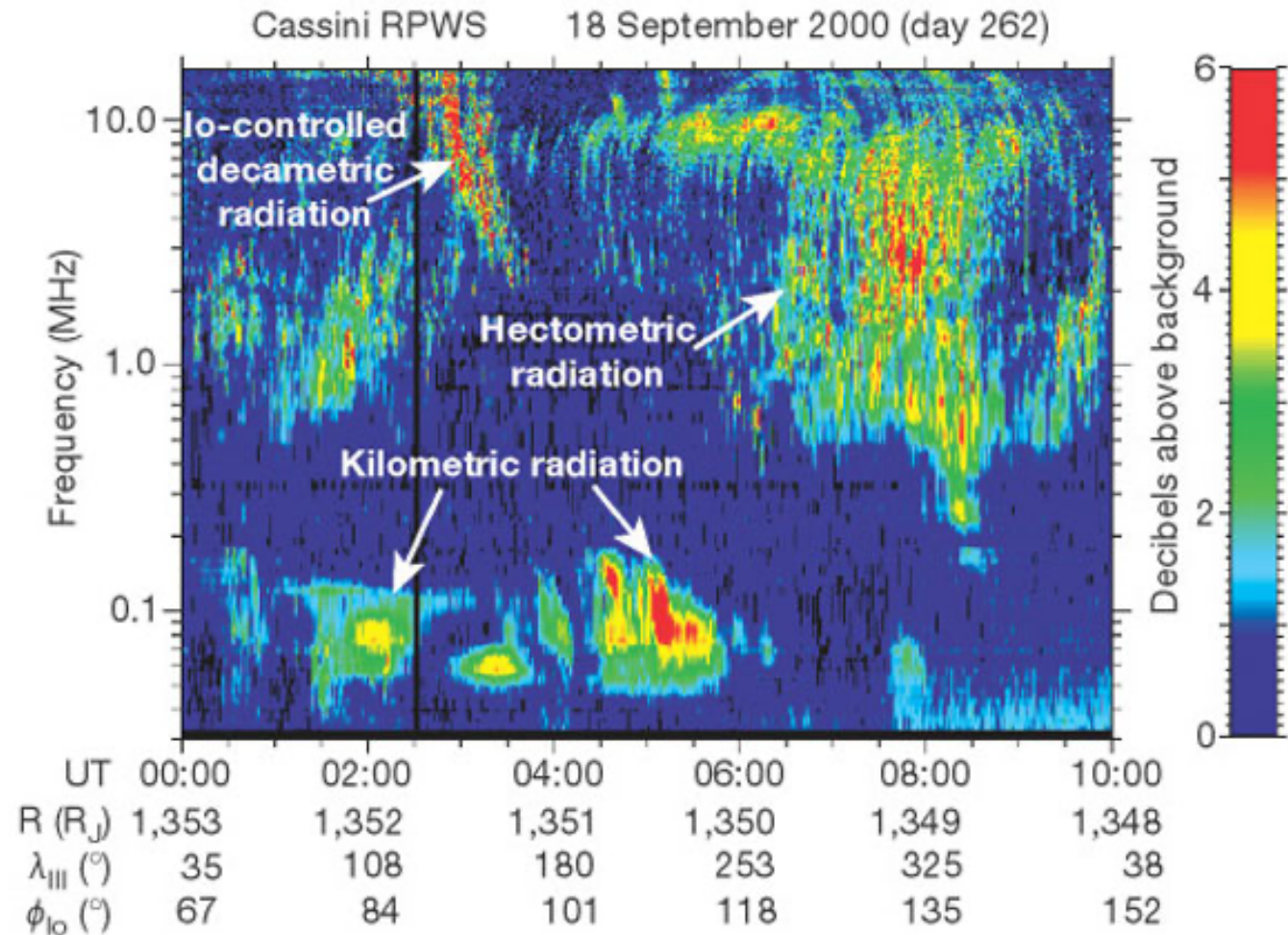
~ 1% of auroral input energy into electron cyclotron maser radio emission

➤ **Can also be driven by magnetosphere-moon interactions**



Planetary Radio Emission

Jupiter

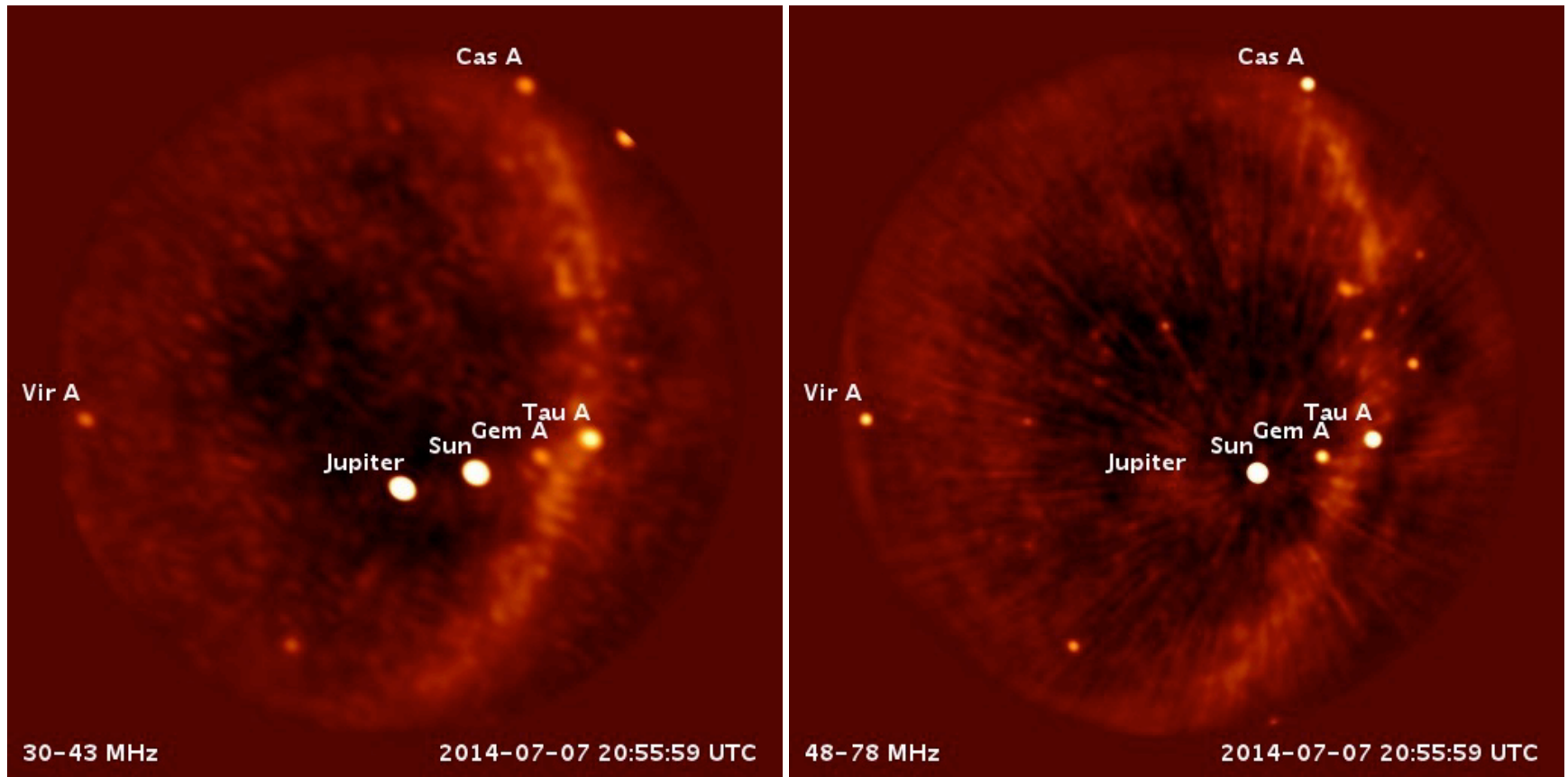


- All gas giants and Earth have strong planetary magnetic fields and auroral / polar cyclotron emission.

Jupiter: Strongest at 10^{12} W

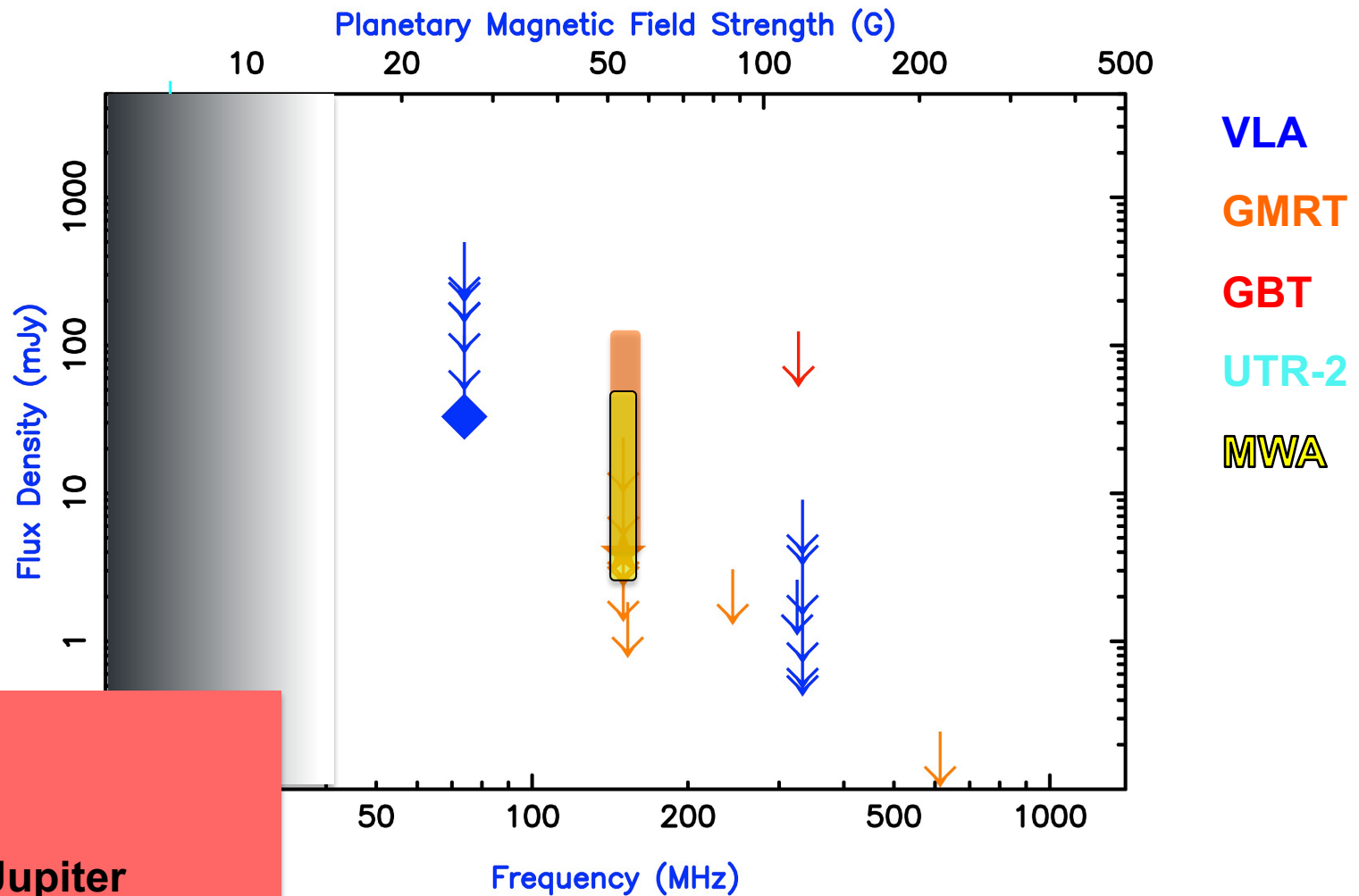
Planetary Radio Emission

Jupiter – and What We Want To See for an Extrasolar Planet!



Credit: M. Anderson

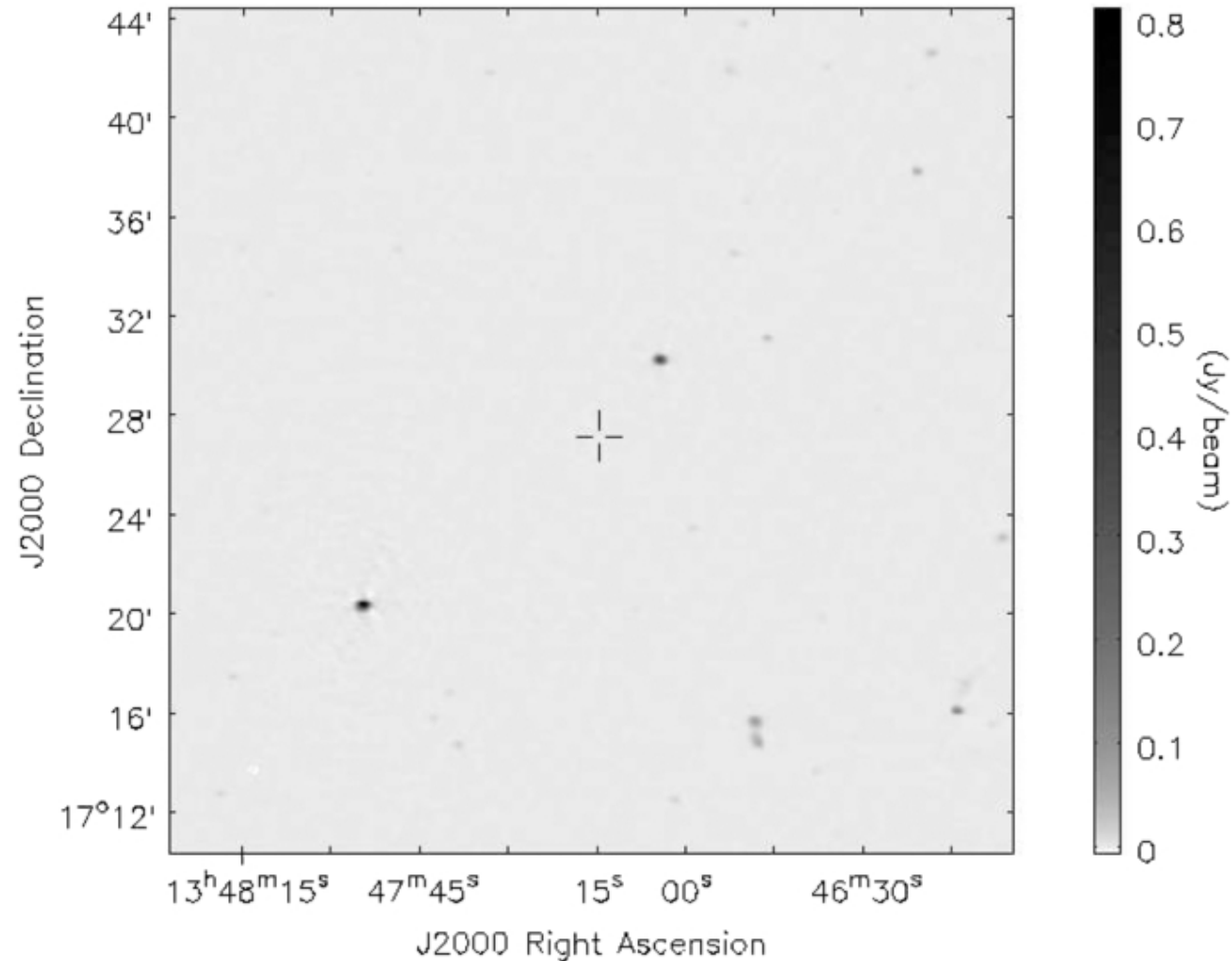
Radio Searches – State of the Field



Radio Searches - State of the Art

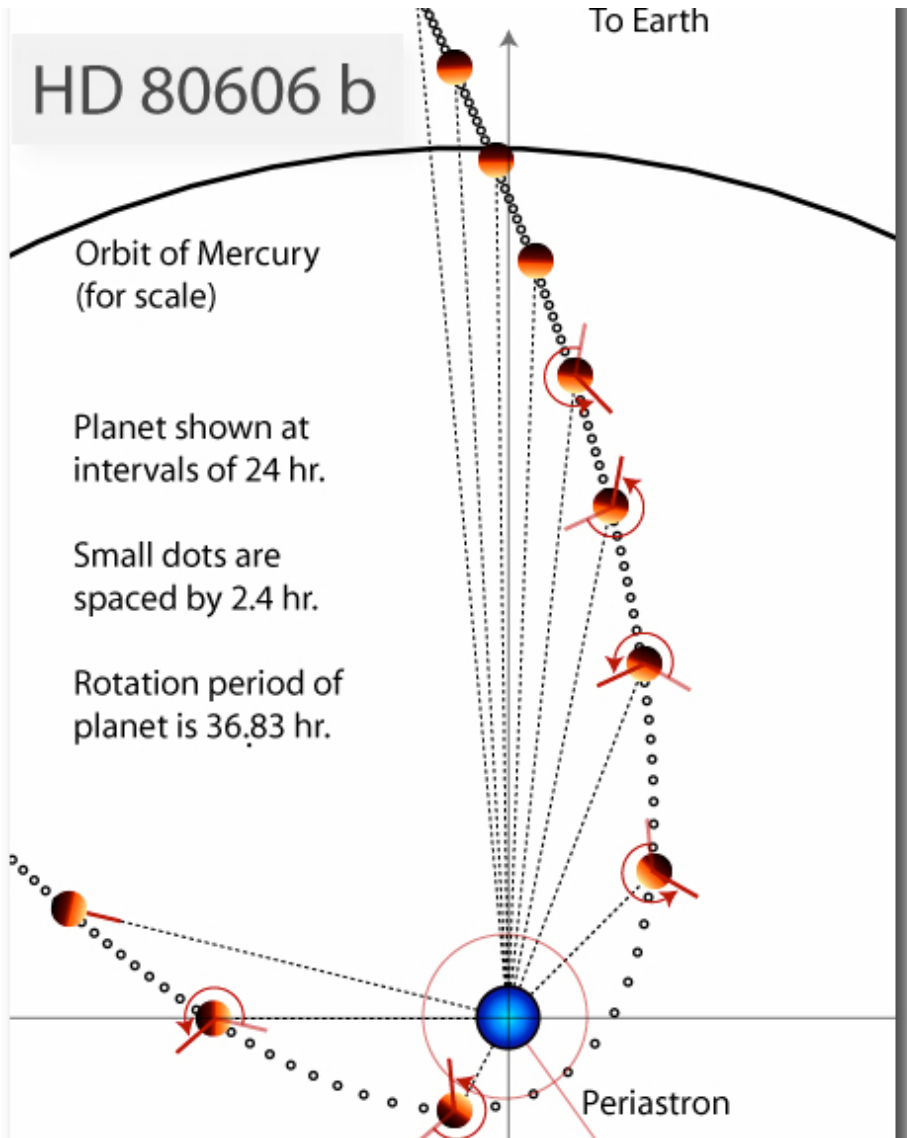
GMRT Observations of τ Boo b

$\sigma_l = 0.35$
mJy/beam



Hallinan et al. 2013

HD 80606b



G5 star

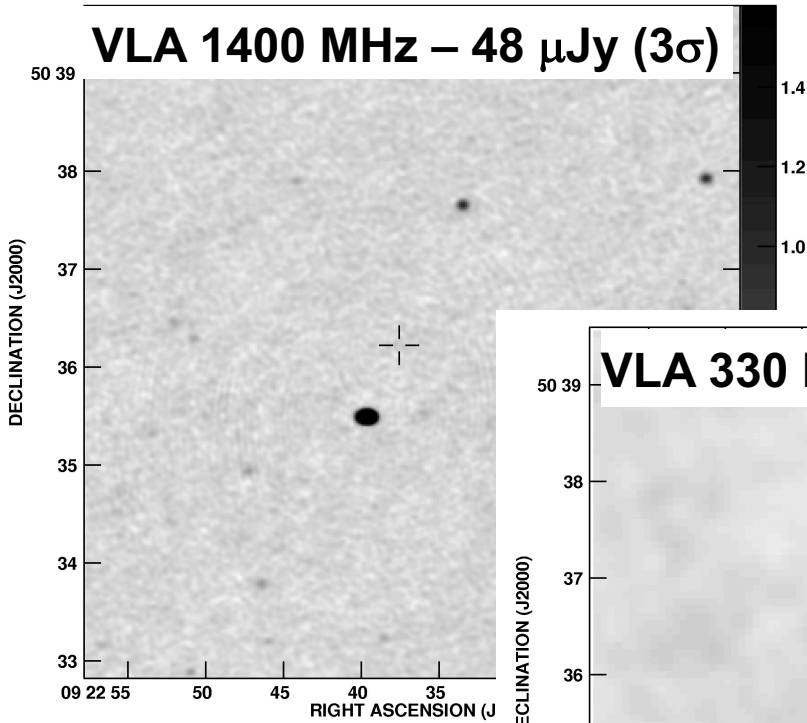
**4 M_J planet, 111-day
orbit**

$e = 0.93$ (!)

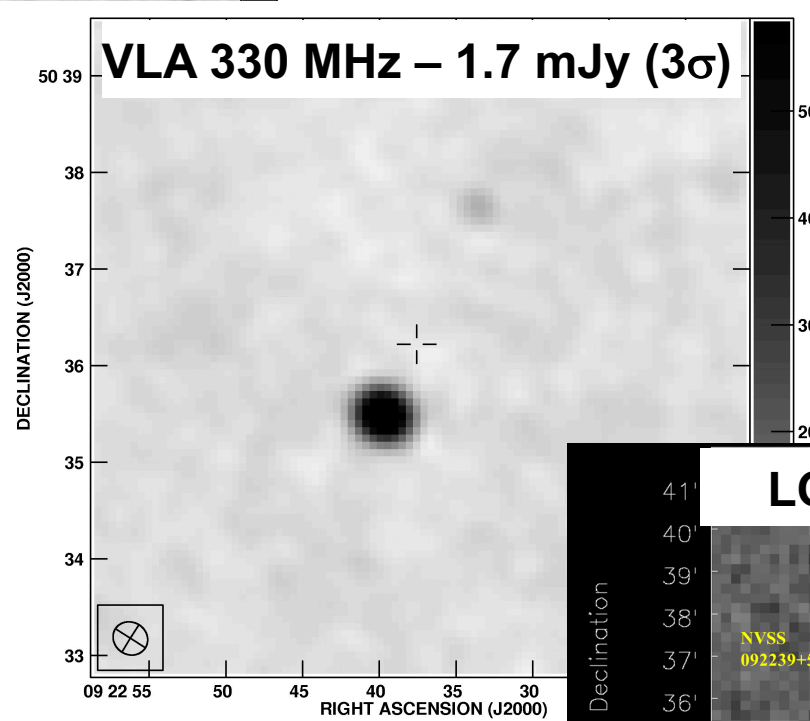
$D = 56$ pc ☹

HD 80606b

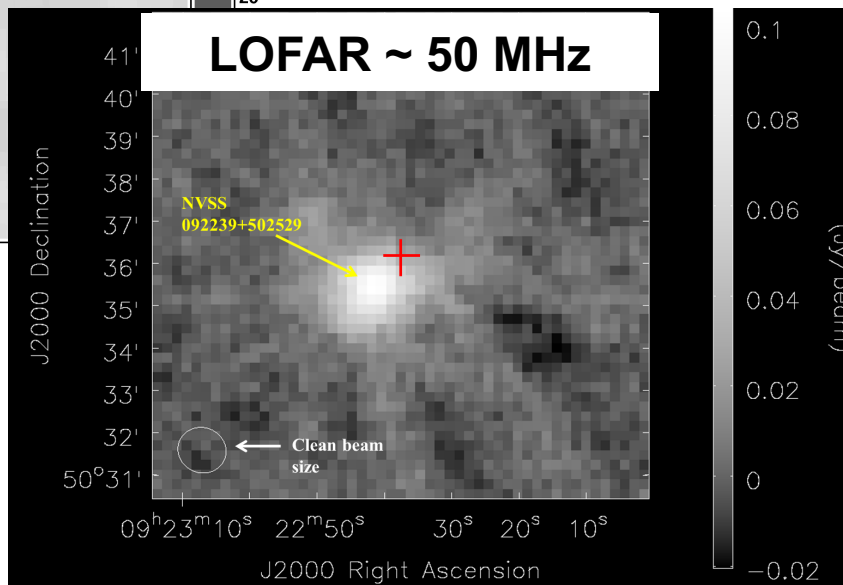
VLA 1400 MHz – 48 μJy (3σ)



VLA 330 MHz – 1.7 mJy (3σ)



LOFAR ~ 50 MHz



Blind Search of the Solar Neighborhood

Sample	Flux Density (3σ , mJy)	Luminosity (erg/s)	Stellar Wind Amplification Factors					K.E. * Jupiter	M.E. * Jupiter
			v	n	B	nv^3	vB^2		
NStars	17	9×10^{23}	1.7	9.8	2.4	48	9.5	4.8×10^{20}	9.5×10^{19}
SPOCS -age	33	1.1×10^{24}	1.4	4.9	1.8	15	4.8	1.5×10^{20}	4.8×10^{19}
SPOCS -eage	28	5.1×10^{23}	1.6	8.6	2.2	38	8.3	3.8×10^{20}	8.3×10^{19}
GCS- age	18	7.3×10^{23}	1.6	6.7	2.0	25	6.5	2.5×10^{20}	6.5×10^{19}
GCS- eage	14	5.8×10^{23}	2.2	30	3.6	319	28	3.2×10^{21}	2.8×10^{20}

From nearby
star catalogs,
select

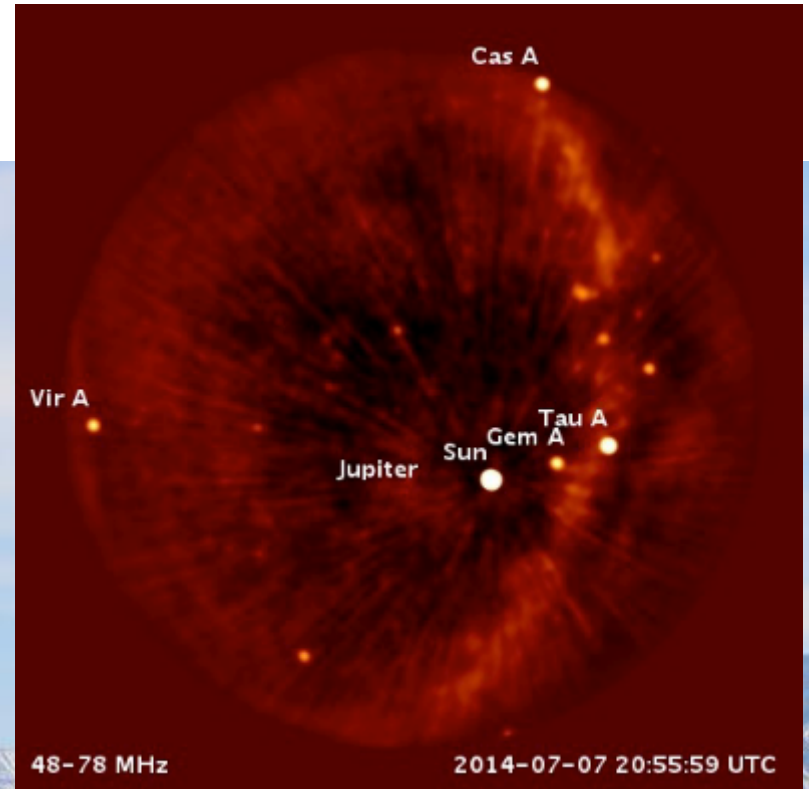
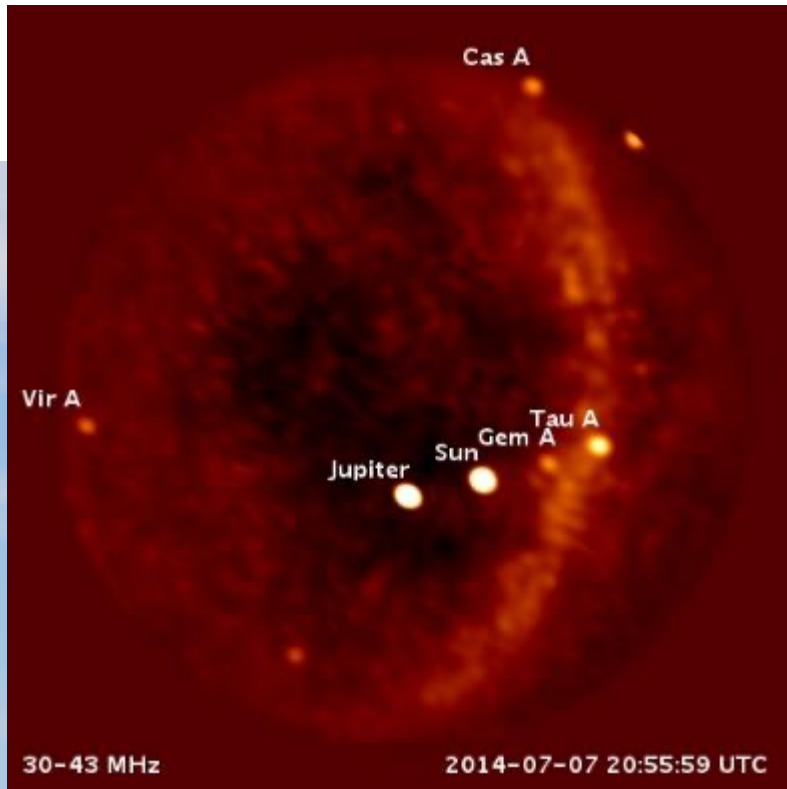
- F, G, K stars
- Age < 3 Gyr
- $D < \sim 40$ pc

Required
for
detection

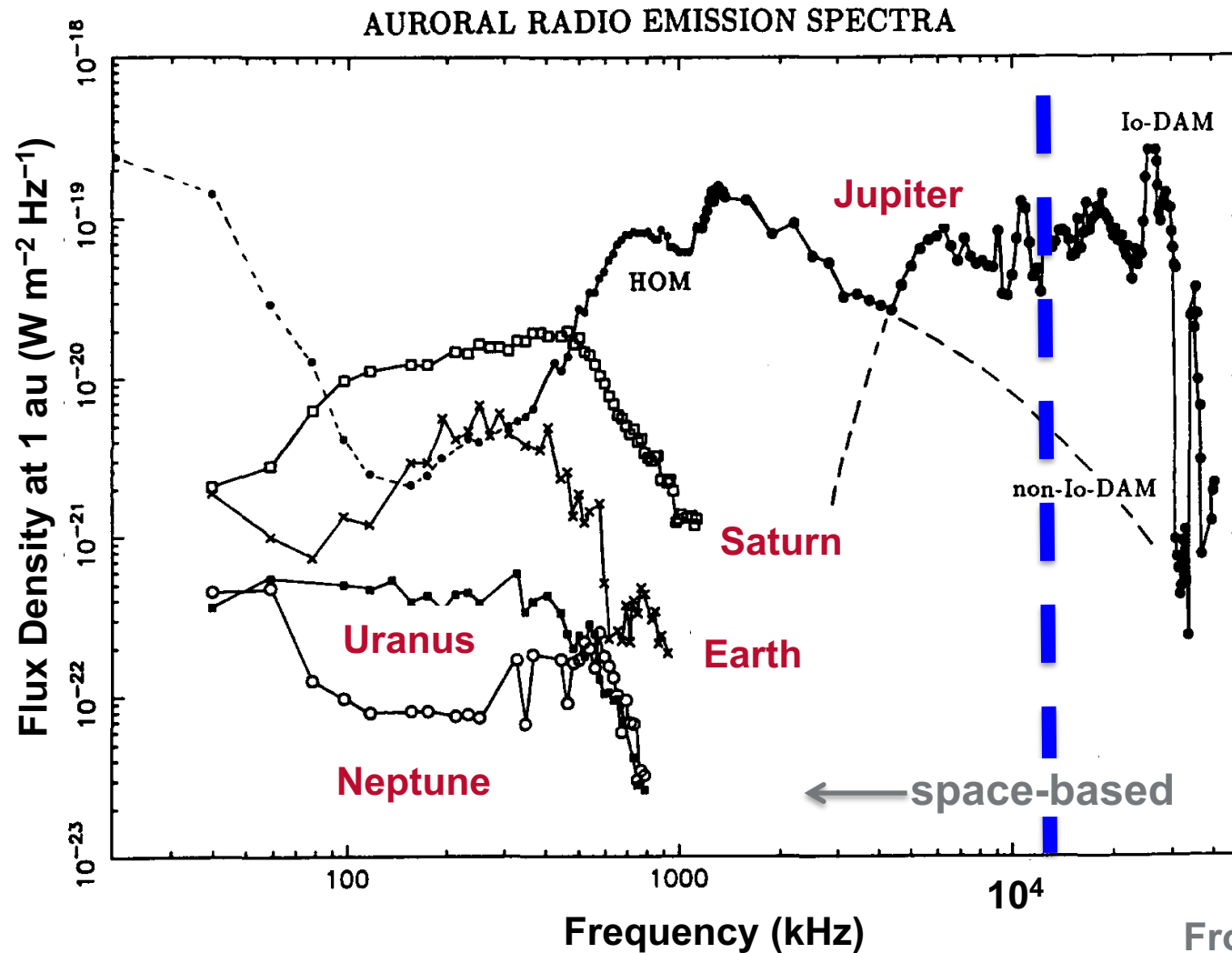
Jupiter's
scaled
luminosity

Act III: Future

Today: LWA-OVRO

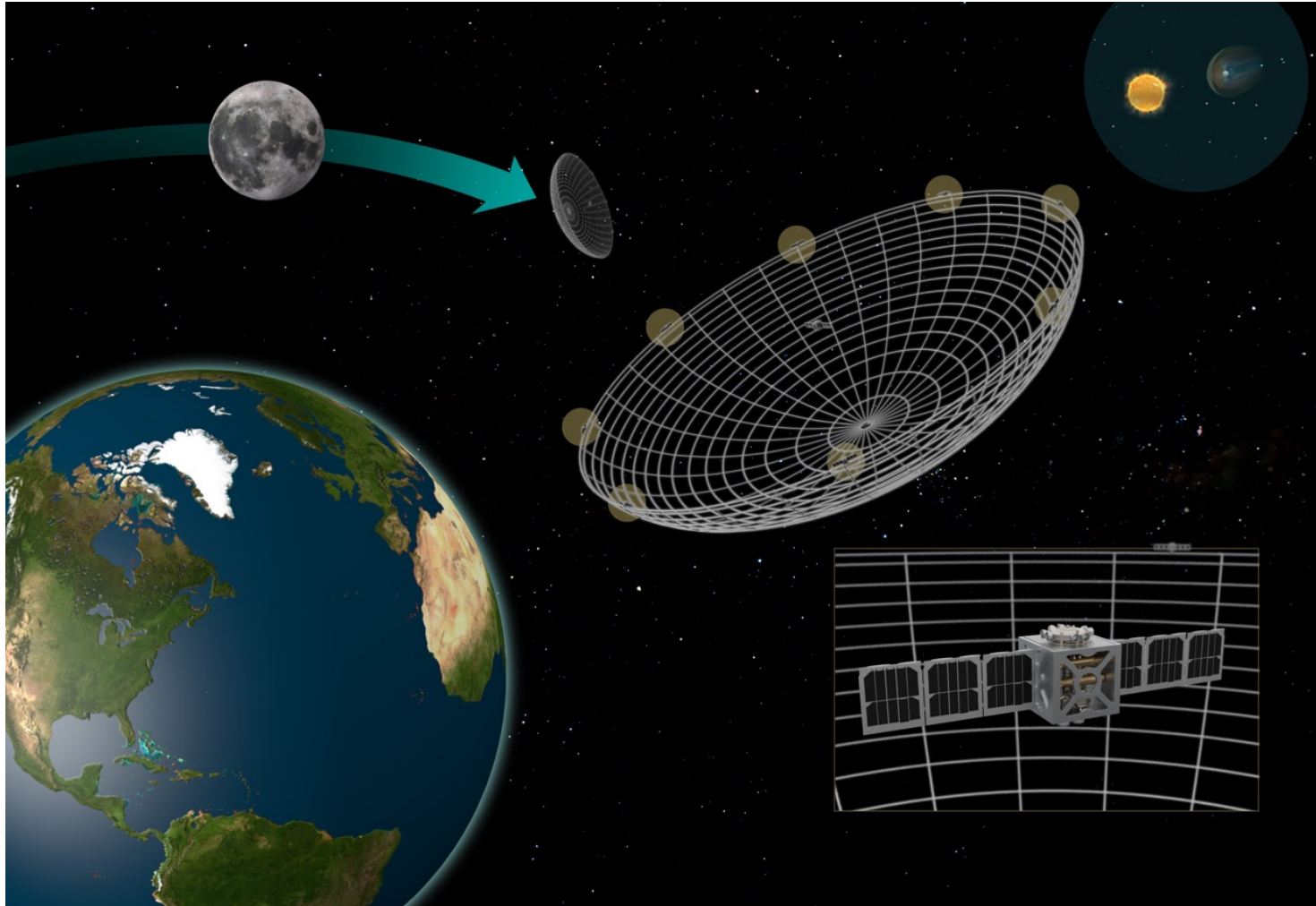


Magnetic Emissions from Solar System Planets

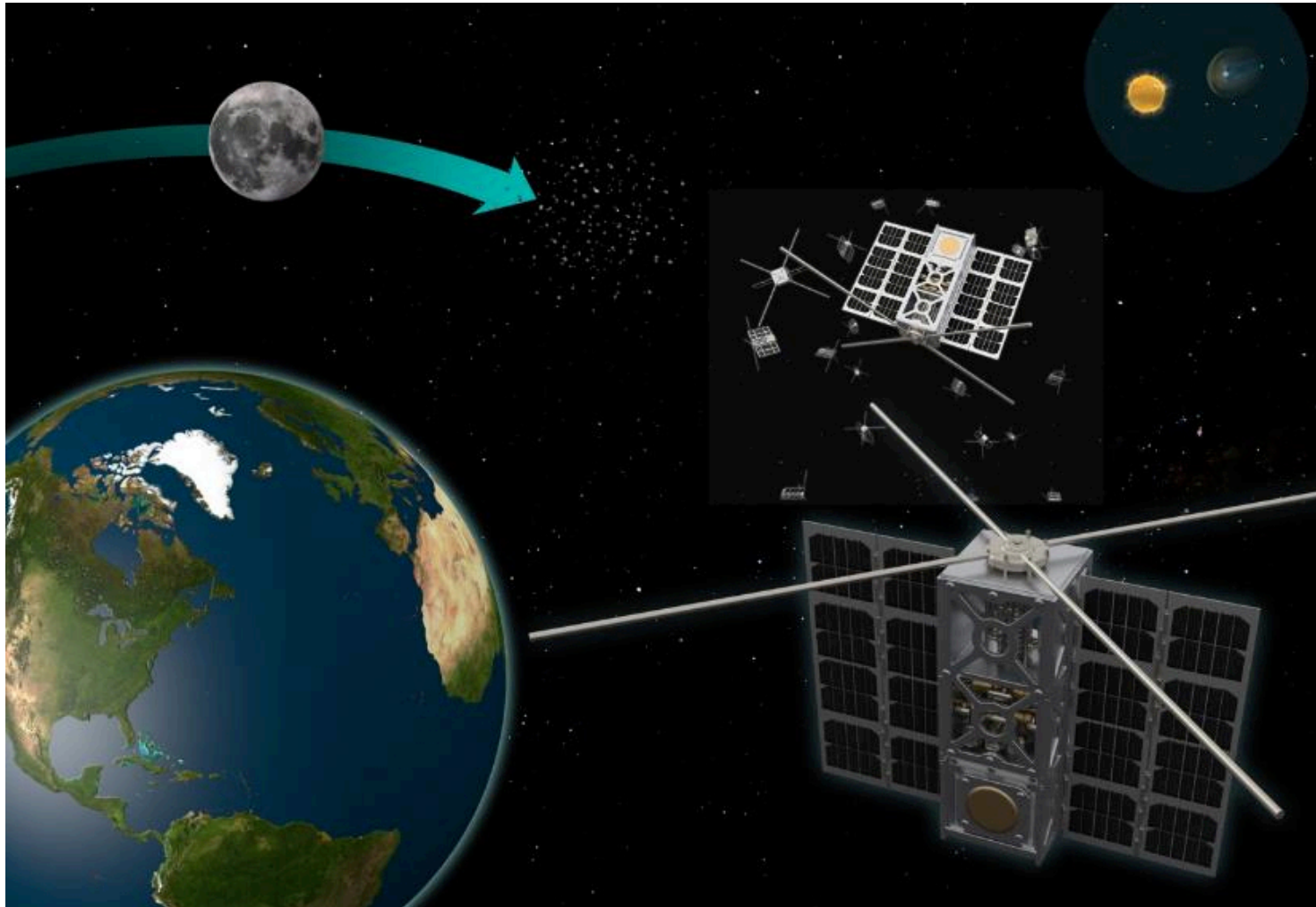


From Zarka (1992)

Tomorrow: Big Aperture Radio Telescope?

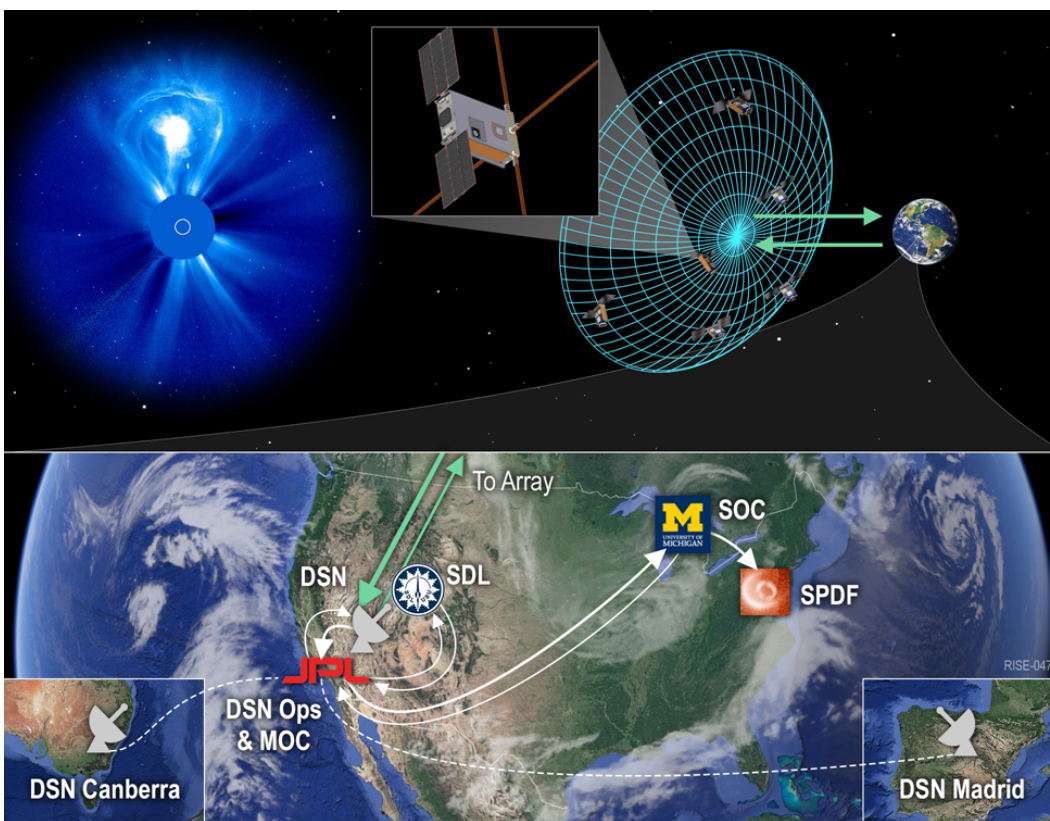


Tomorrow: Radio Array in Space?



Sun Radio Interferometer Space Experiment

Breaking News!



Launch	2024 March (TBC)
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Selected for Extended Phase A study	2019 February 25
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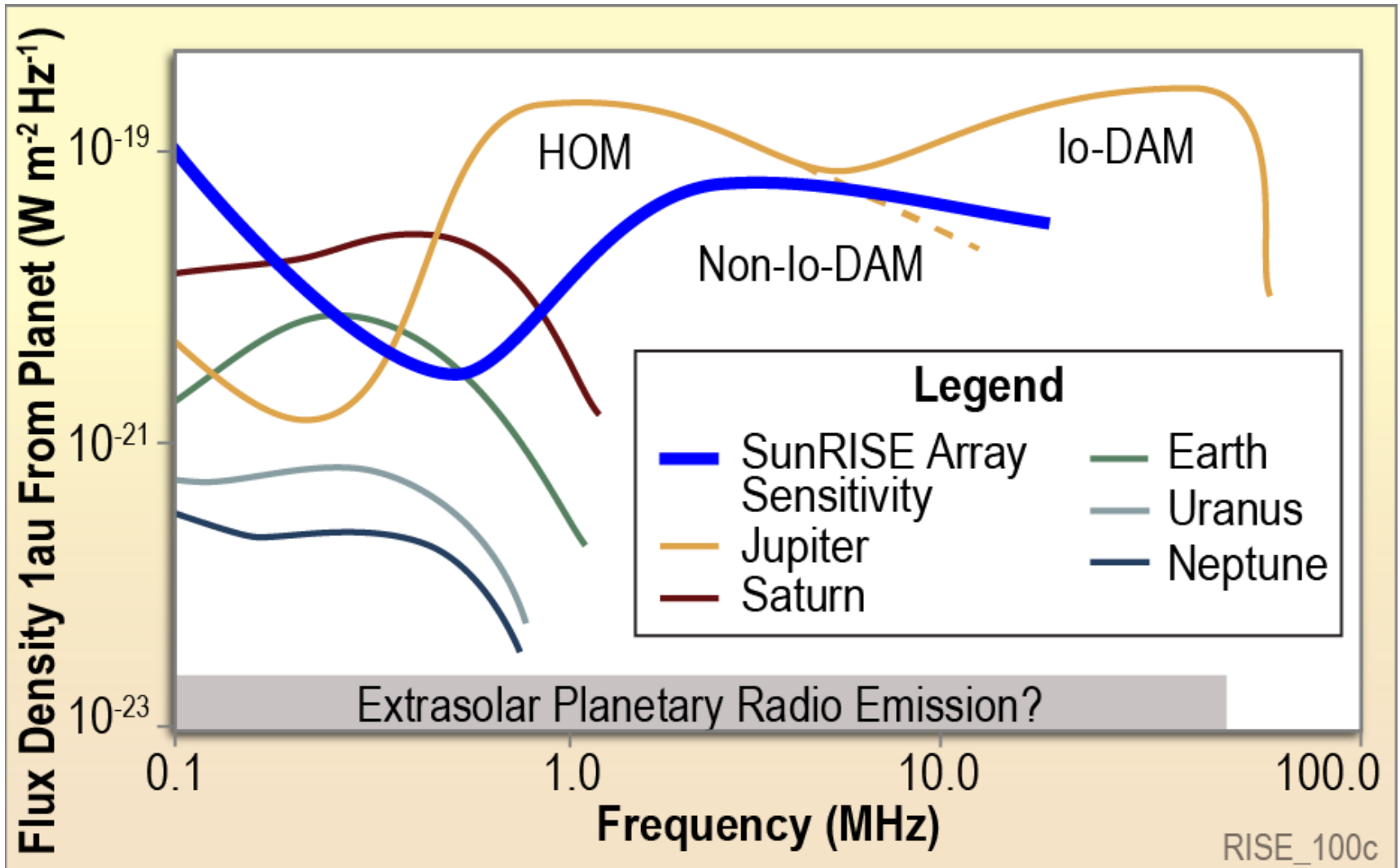
Phase A Concept Study report	2018 July 30
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Selected for Phase A study	2017 July 28
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SunRISE proposal submitted (NASA/Heliophysics SALMON-2 PEA Q/MOO SCM)	2016 October 14
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NASA/Heliophysics Announcement of Opportunity	ca. 2016 July
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SunRISE – The Planet Hunter



“Nothing New Under the Sun”

Q35-5 A Search for Extra-Solar Jovian Planets by Radio Techniques. W.F. YANTIS, U. Wash. and Goldendale Observatory, W.T. SULLIVAN, III, U. Wash. & W.C. ERICKSON, U. Maryland. - We propose to search for the presence of planets associated with nearby stars through detection of Jovian like decametric radio bursts. Planetary bursts would be distinguished from possible stellar bursts by the presence of a high-frequency cut-off and possibly a modulation associated with the rotation of the planet. A search for such planetary radio bursts at 26.3 MHz is presently being conducted at The Clark Lake Radio Observatory. The sample includes 22 stars within 5 parsecs. The sensitivity limit is 10^{-26} watts m^{-2} Hz^{-1} , about 1,000 times the signal expected from a strong Jovian burst. However, it is expected that the strength of any bursts will depend strongly on the planetary magnetic field and also possibly on the presence of a stellar wind. Initial observations exhibit several non-instrumental features which are under current study. Further results will be reported and monitoring observations are continuing.

“A Search for Extra-Solar Jovian Planets by Radio Techniques” (Yantis, Sullivan, & Erickson 1977)

- Soon after recognition that Saturn also intense radio source
- Earth, Jupiter, Saturn

“A Search for Cyclotron Maser Radiation from Substellar and Planet-like Companions of Nearby Stars (Winglee, Dulk, & Bastian 1986)

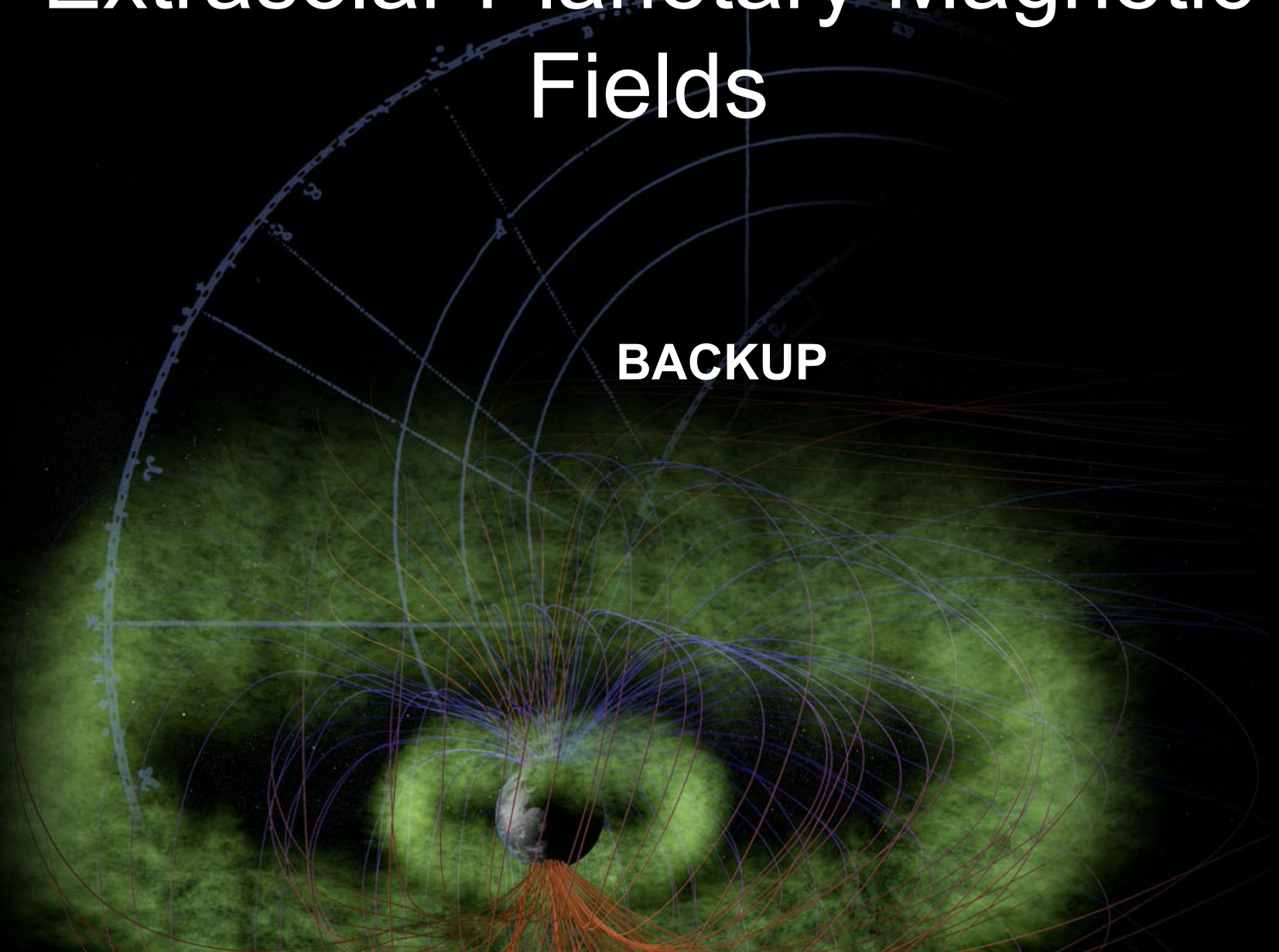
Extrasolar Planetary Magnetic Fields

- Magnetic fields provide probe of planetary interiors
 - Both solar system and extrasolar!
- Atmospheric retention (and habitability) influenced by presence of magnetic fields
 - Other confounding factors?
- Magnetospheric radio emissions are unique probe
 - Will require ground-based experience to inform future space missions

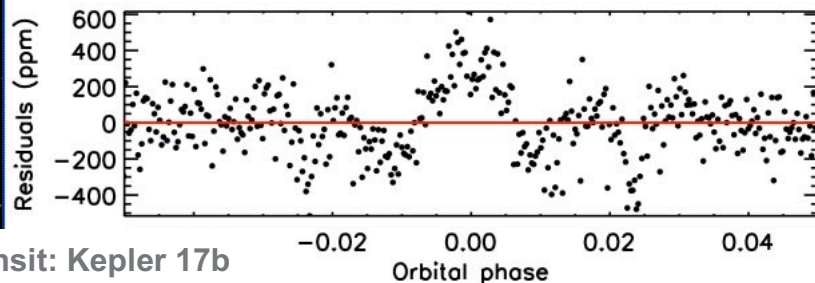
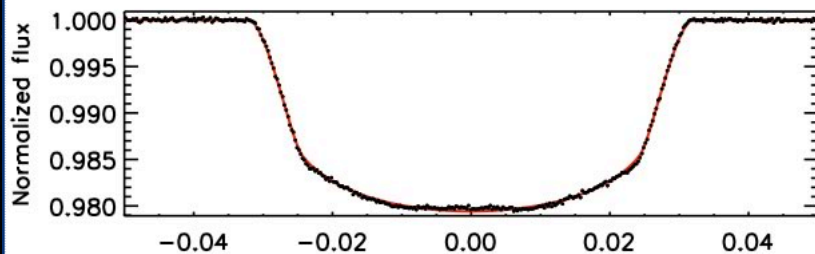
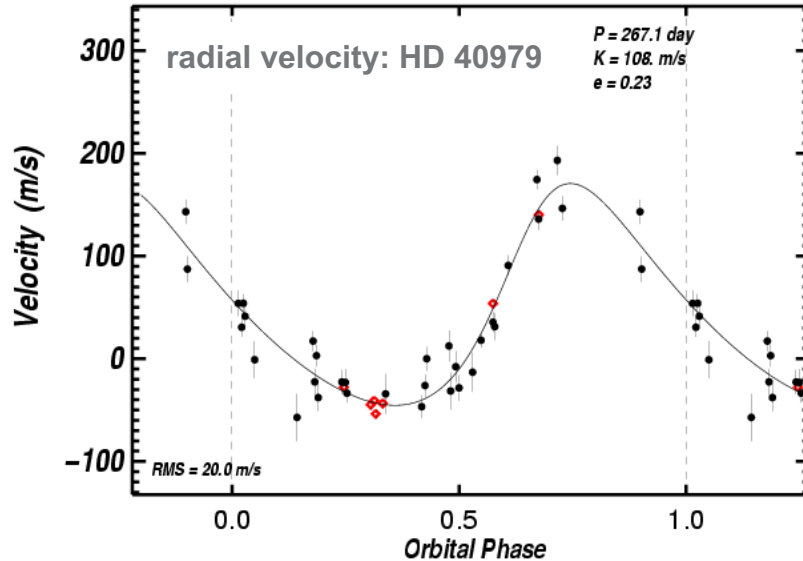


Extrasolar Planetary Magnetic Fields

BACKUP



Introduction



transit: Kepler 17b

In last decade, exciting discovery of extrasolar planets

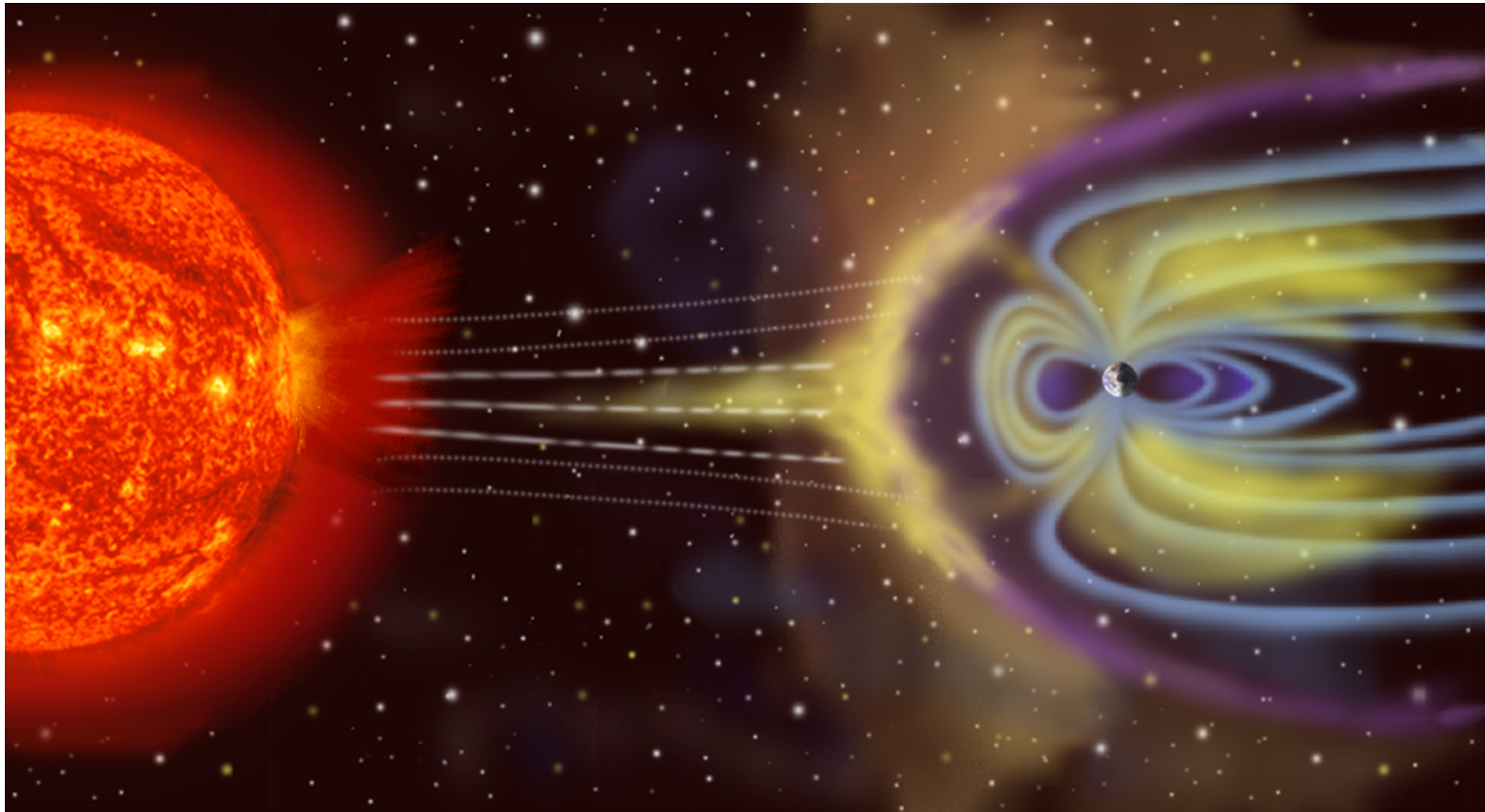
~ every star hosts a planet

➤ Most are indirect detection via optical signature from host star

“Do there exist many worlds, or is there but a single world? This is one of the most noble and exalted questions in the study of Nature.”

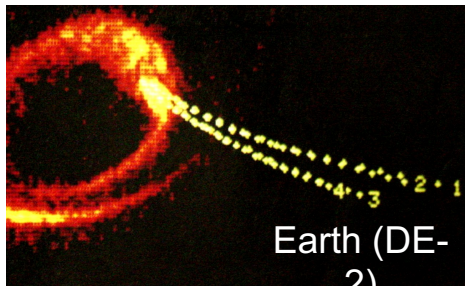
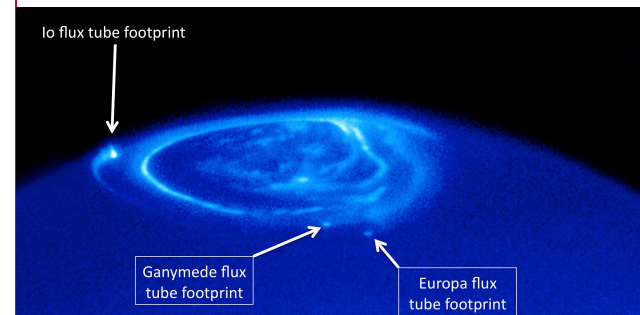
St. Albertus Magnus, *De Caelo et Mundo* (13th century)

Stellar-Planetary System

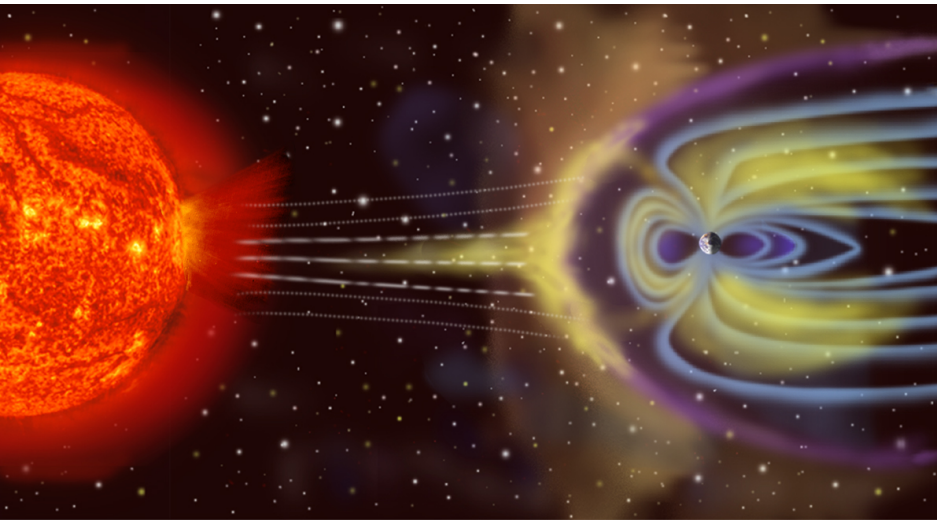


Stellar wind provides energy source to magnetosphere

- Coupled system, have to understand star and planet together?

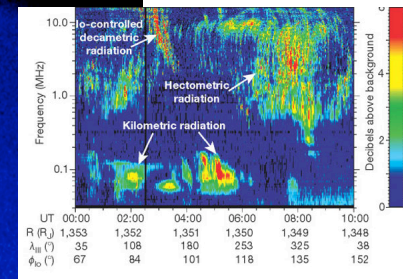
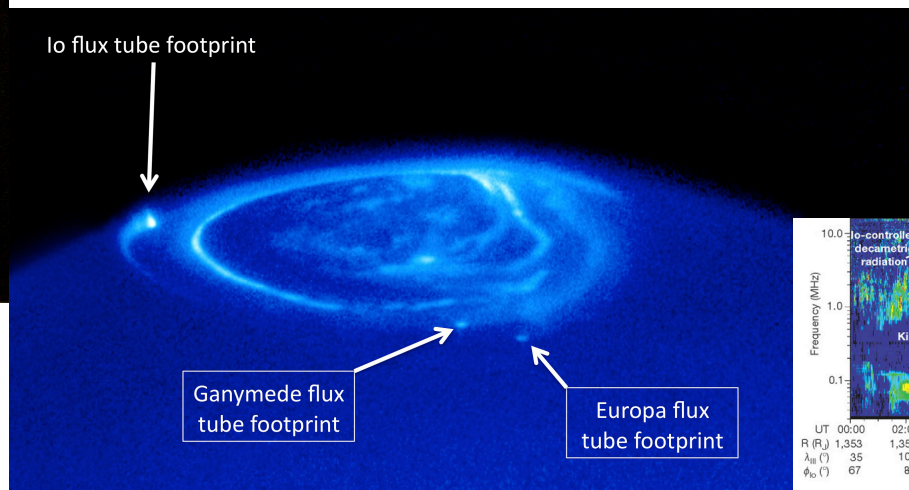
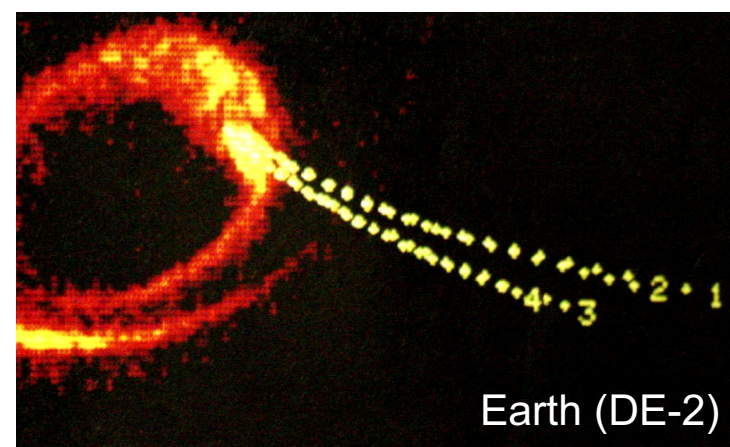


Magnetic Fields in Extrasolar Planets

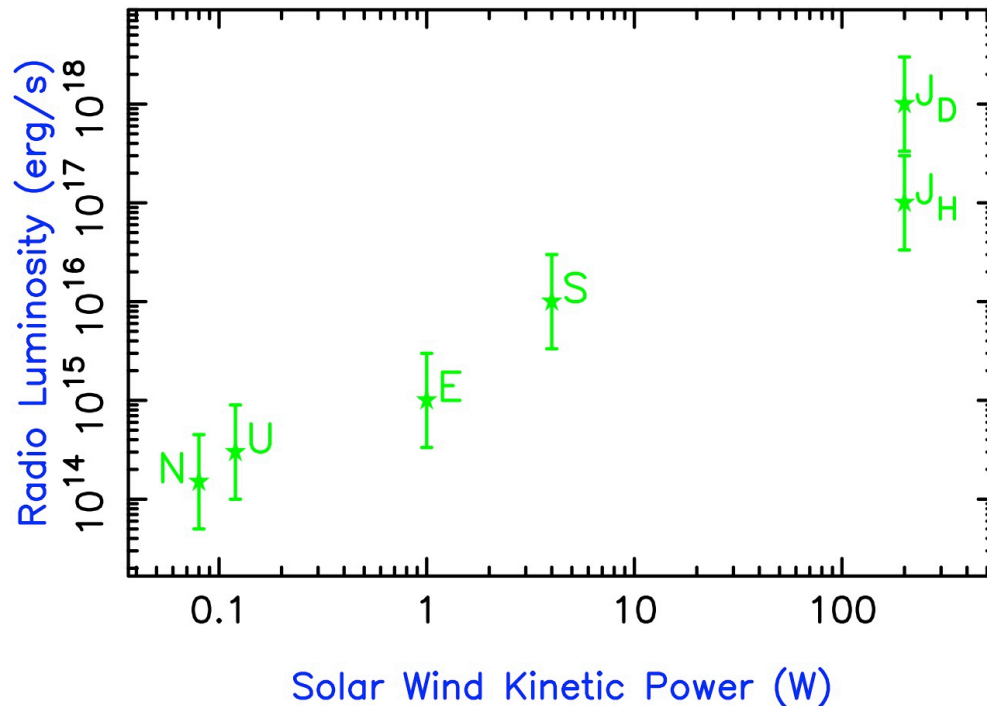


planets can generate large-scale magnetic fields

- Stellar wind provides energy source to magnetosphere
- Provides means for detection and characterization of extrasolar planets
 - Transit light curve variations
 - Auroral H_2 emission lines
 - Auroral electron cyclotron masers



Radiometric Bode's Law



Correlation between planetary radiated power (P_{rad}) and input solar wind power (P_{sw})

$$P_{\text{rad}} \sim \varepsilon P_{\text{sw}}^x$$

$$x \sim 1$$

$$\varepsilon \sim 10^{-6} \text{ to } 10^{-3}$$

- Desch & Kaiser (1984) **predicted** Uranus' radio power before 1986 Voyager encounter
- Zarka et al. (1997) refined by adding Uranus, Neptune, and non-Io DAM.

HD 80606b

- $3.94 \pm 0.11 M_J$ planet
- $0.98 \pm 0.03 R_J$
- 111-day orbit
- $e = 0.93$
- $T = 39$ hr (rotation period)
- $\nu \sim 55 - 90$ MHz

Frequency	Luminosity
1425 MHz	2.7×10^{23} erg/s
330 MHz	2.3×10^{24} erg/s
~ 50 MHz future?	$< \sim 10^{23}$ erg/s

Future =? few mJy

- EVLA-Io @ 70 MHz
- LOFAR @ 60 MHz

Magnetosphere Emissions



Very Large Array



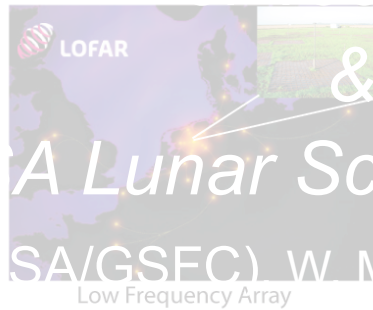
Giant Metrewave Radio Telescope



Ukrainian T Radiotelescope



Long Wavelength Array



Low Frequency Array

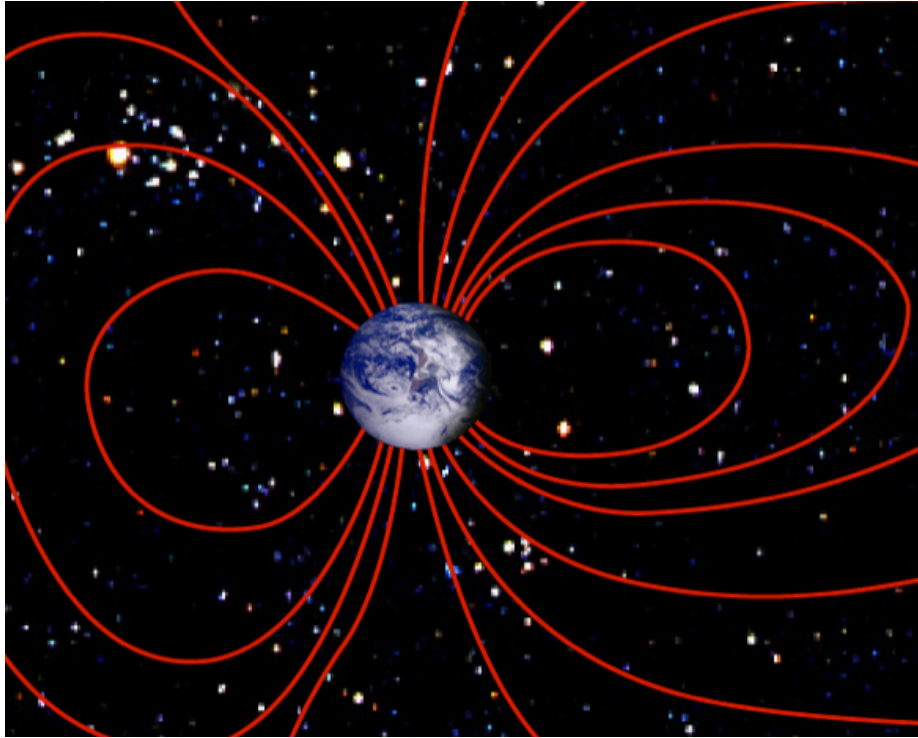


Square Kilometre Array



lunar radio array

Planetary Magnetic Fields



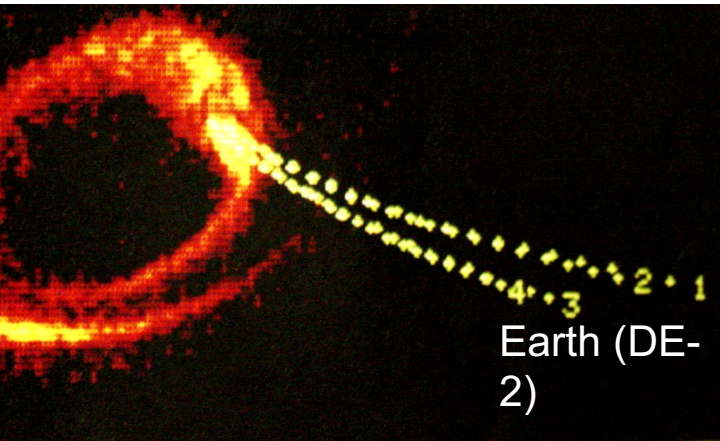
Planetary-scale magnetic fields

Earth, Jupiter, Saturn, Uranus, & Neptune (Mercury)

- Produced by rotation of conducting fluid
 - Earth: liquid Fe core
 - Jupiter & Saturn: metallic H₂
 - Uranus & Neptune: salty oceans
- So what?
 - Magnetic field composition
 - Rotation period
 - Difficult to determine by other means
 - Defined by magnetic field for solar system giant planets
 - Existence of satellites
 - Atmospheric retention
 - Habitability

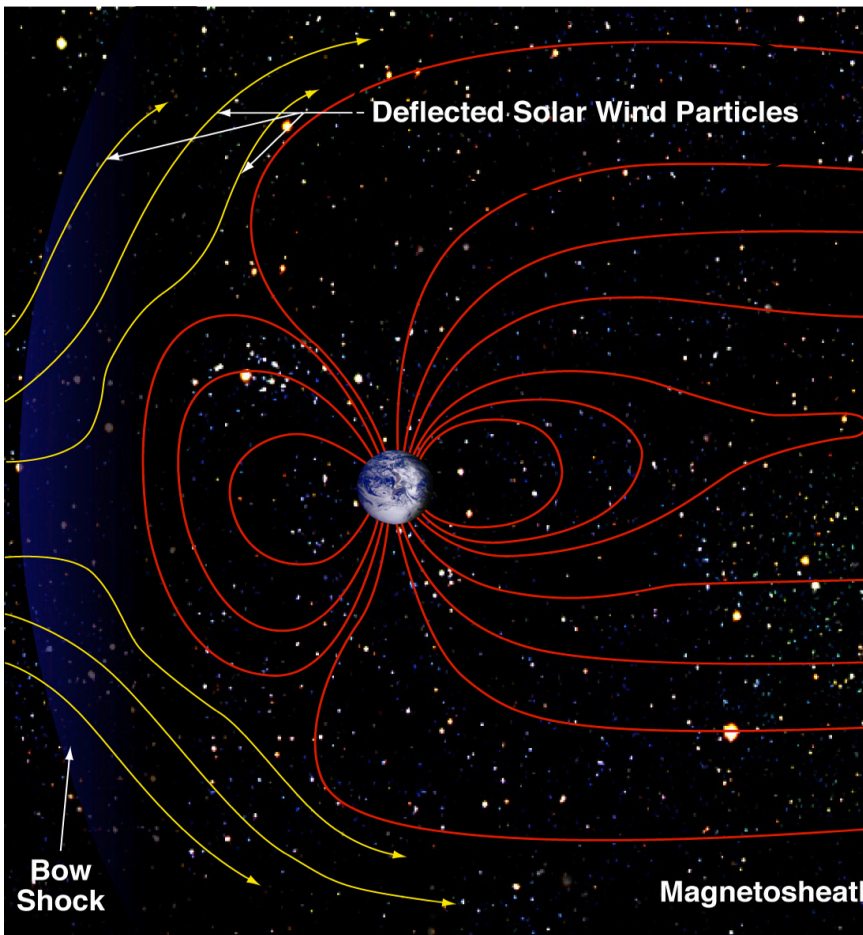
Planetary Radio Emission

From Magnetosphere to Pole



- Solar wind loading of magnetosphere produces radio emission
- 1% of auroral input energy into electron cyclotron radio emission (Gurnett 1974)
- Auroral radio sources typically map directly to auroral optical sources (Huff et al. 1988)

Magnetospheres and Habitability



Solar wind particles (with supra-thermal velocities) deflected at magnetosphere

- Protects the atmosphere — thermal vs. nonthermal escape
 - Thermal: Does molecular thermal velocity exceed planetary escape velocity?
freshman physics problem
 - Nonthermal: collisional physics sputtering, mass loading, ...
 - Water retention?
- Affects the planet's albedo
- May protect genetic material of organisms

Other Observations



- GMRT observations

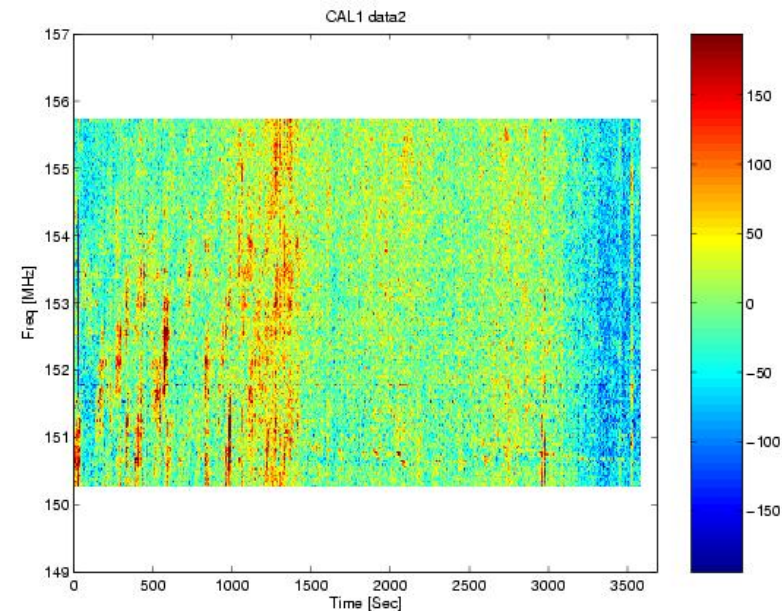
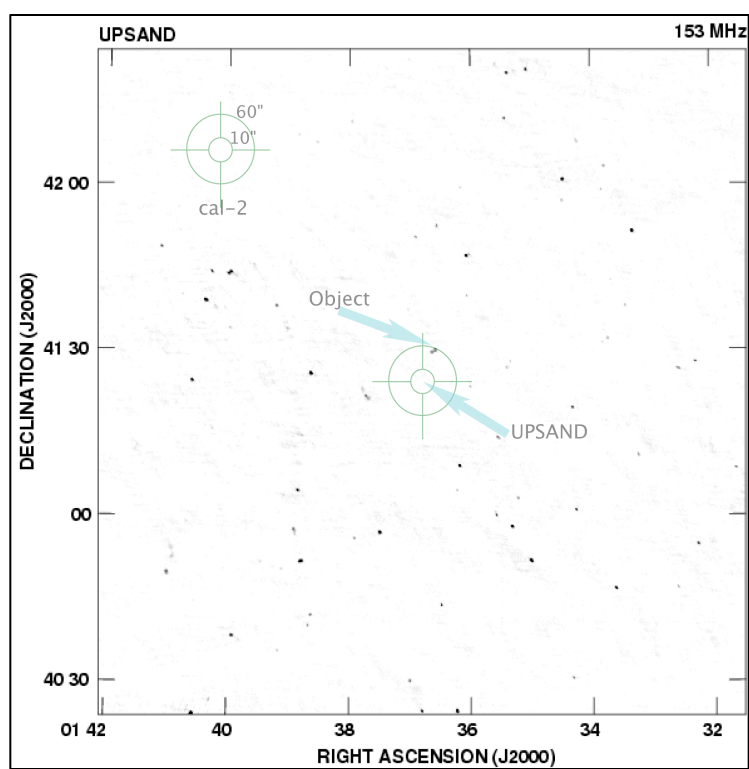
- Stars with confirmed extra-solar planets: τ Boo, 70 Vir, 55 Cnc, HD 162020, HD 174949 @ 150 MHz (Winterhalter, Majid, Lazio, et al.)
- τ Boo @ 150 MHz (Hallinan et al.)
- HD189733b @ 244 and 614 MHz (Lecavelier des Etangs et al.)

- UTR-2

Stars with confirmed extra-solar planets @ 25 MHz (Zarka et al.)

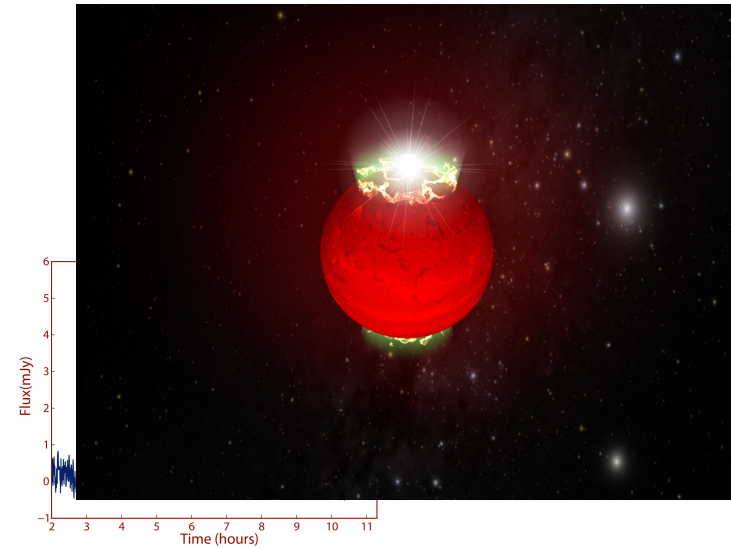
- GBT

HD 189733 b @ 320 MHz (Smith et al.)

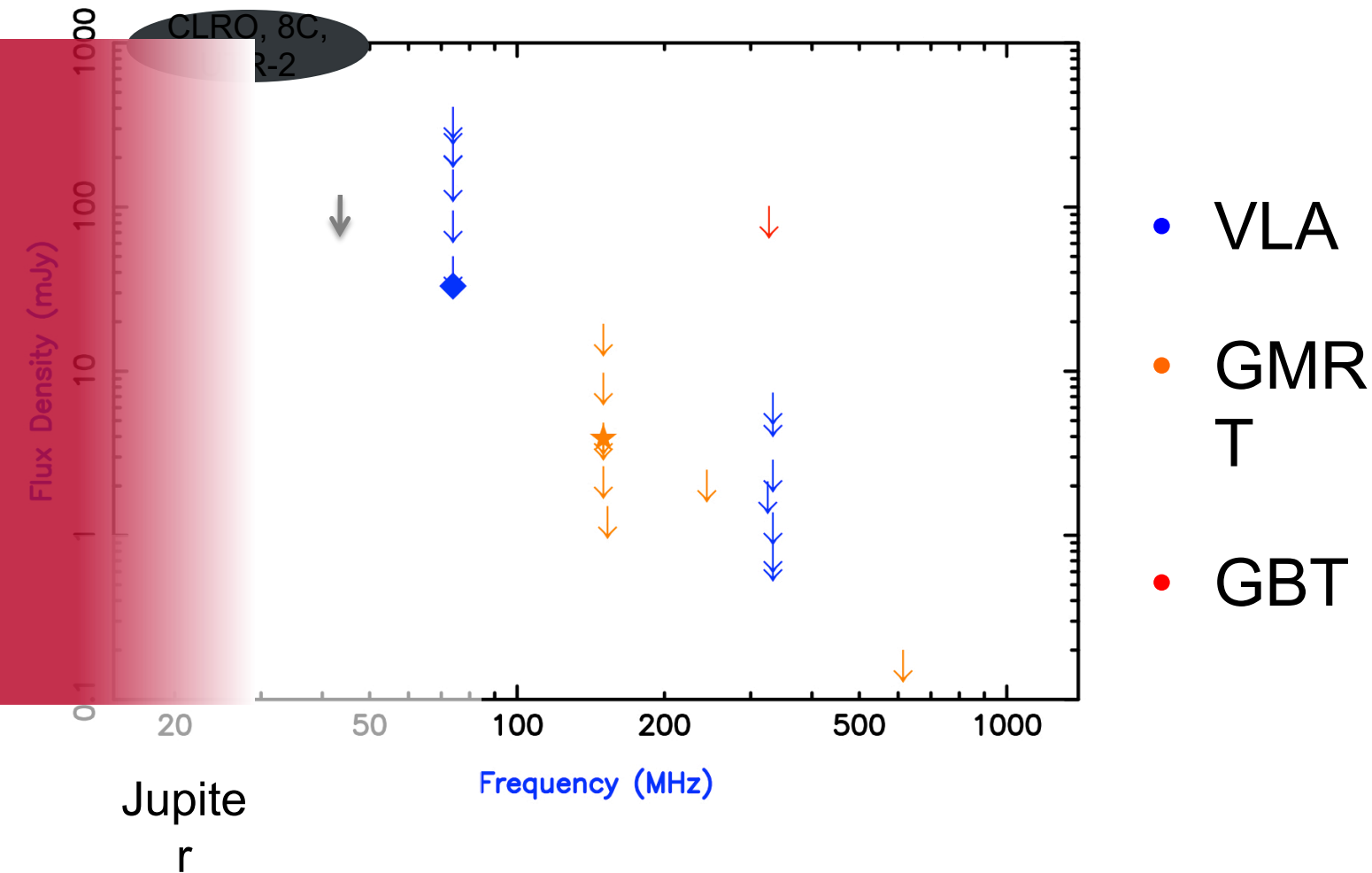


Lighthouse-like Brown Dwarfs

- Low-mass stars, brown dwarfs can be strong radio emitters
- Break the Benz-Güdel relation
 - Radio luminosity far higher than expected given X-ray luminosity
 - cm wavelengths vs. dam wavelengths for Jupiter
- Extrasolar planets?
- VLA has 25 yr of observations ...



Extrasolar Planetary Radio Emission Searches

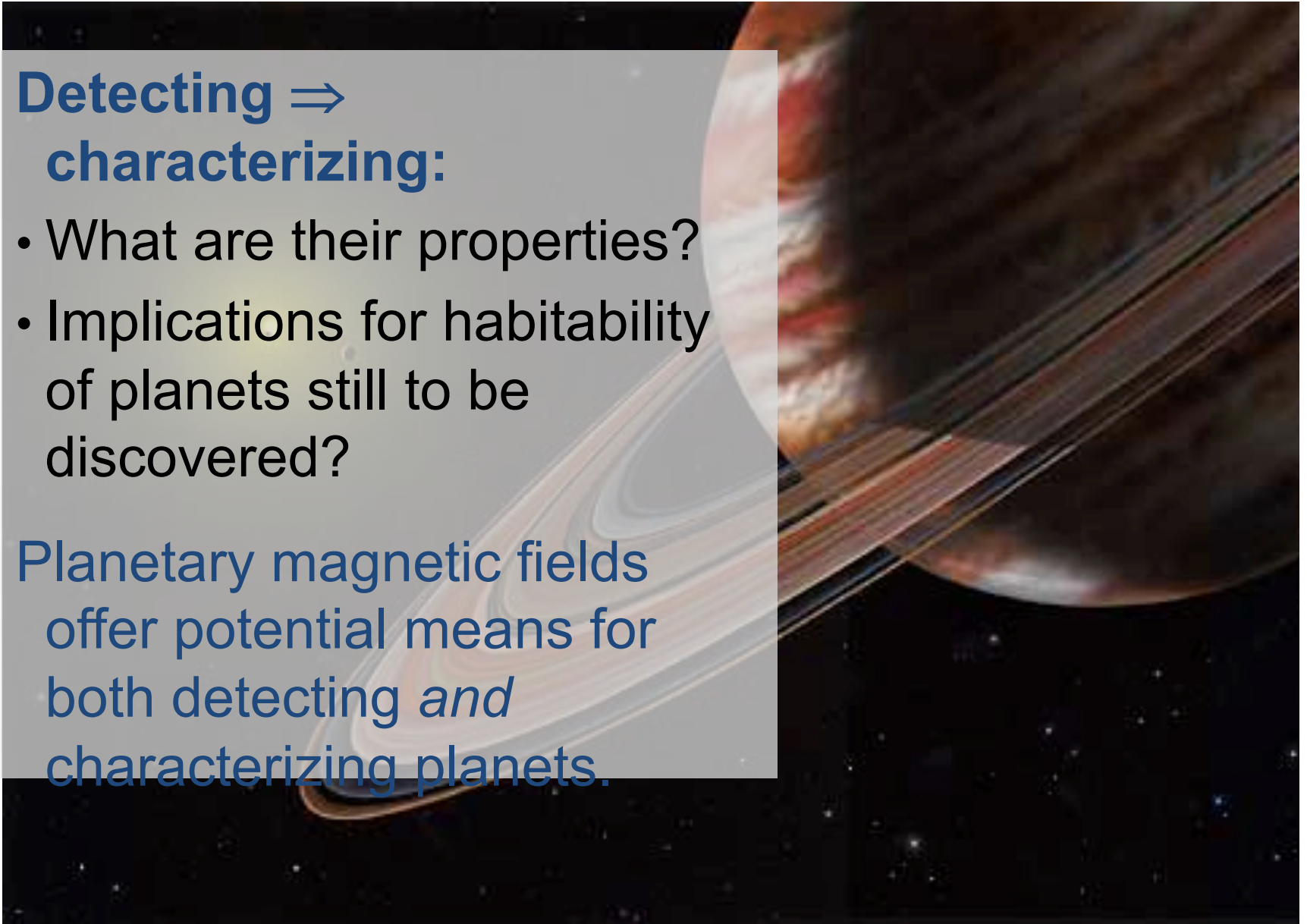


The Next Step

Detecting ⇒ characterizing:

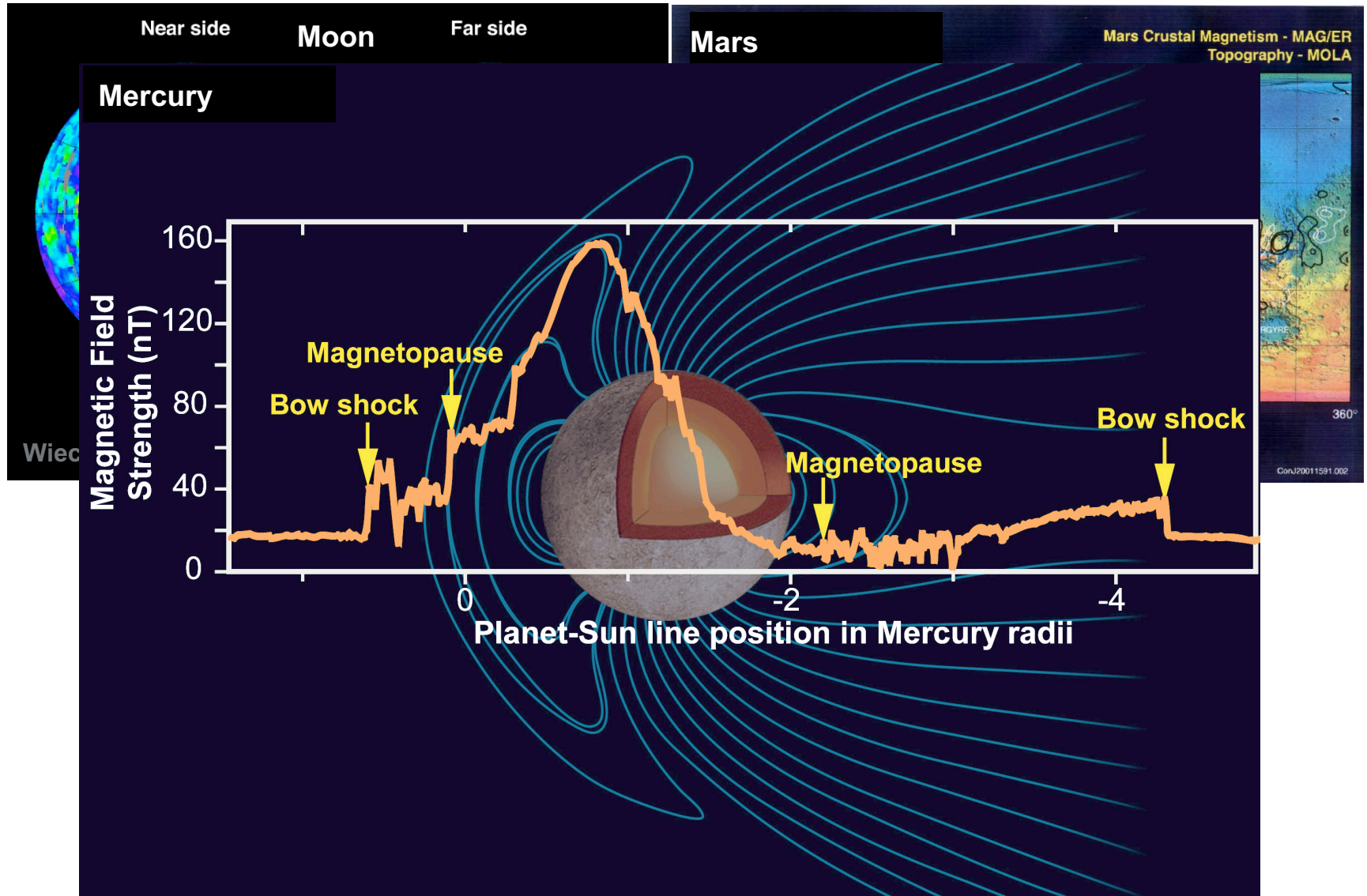
- What are their properties?
- Implications for habitability of planets still to be discovered?

Planetary magnetic fields offer potential means for both detecting *and* characterizing planets.

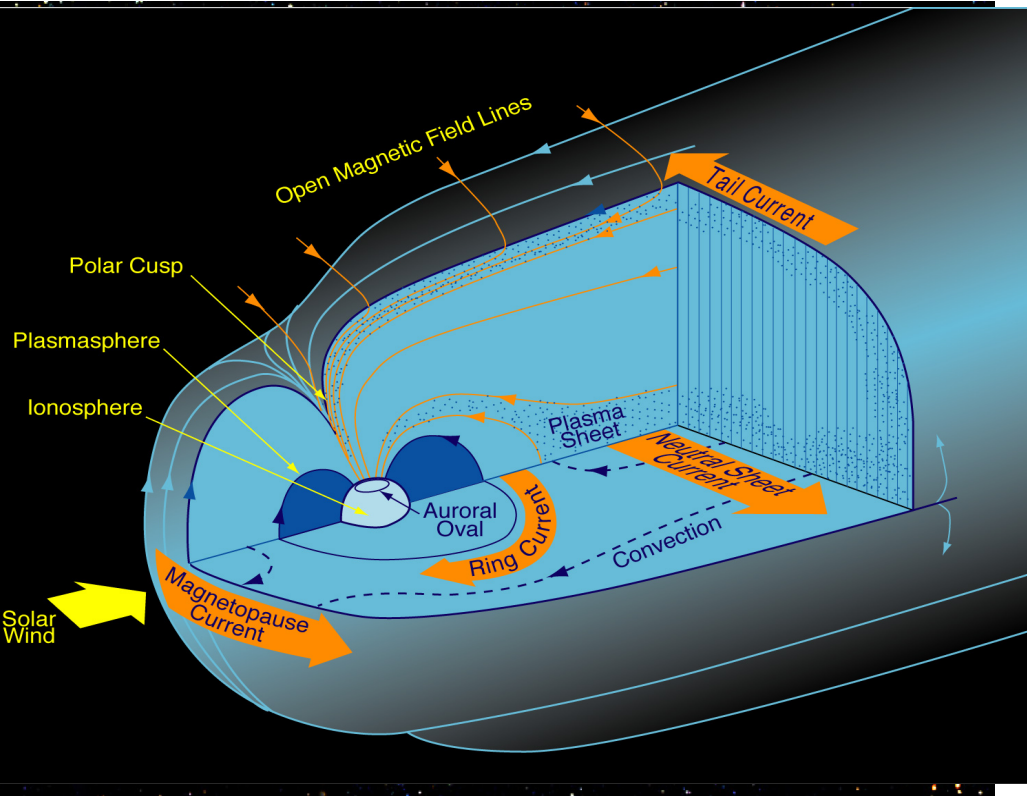


Planetary Interiors and Magnetic Fields

Terrestrial Planets



Planetary Magnetic Fields and Magnetospheres



- Planetary magnetic field immersed in solar wind
- Solar wind is high-speed plasma with embedded magnetic field
- Pressure from solar wind impacts and deforms planetary magnetic field.

➤ Magnetosphere

Large objects, e.g., Jovian magnetosphere is 5× diameter of full Moon

